Indoor air quality in highly energy efficient homes – a review

NHBC Foundation
Housing research in partnership with BRE Trust

ZERO CARBON HUB

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SUMMARY

This review assesses the current state of knowledge on indoor air quality in energy efficient, airtight houses in the UK and elsewhere in the world. It summarises the characteristics of homes built to Levels 4, 5 and 6 homes of the Code for Sustainable Homes, and discusses the relationship between indoor air quality and occupant wellbeing. Research in the UK, Europe and the rest of the world into indoor air quality and other factors which may impact on occupant wellbeing is reviewed. This is followed by a review of current research and state of the art for ventilation performance in dwellings and of construction and ventilation provision in highly energy efficient homes.

Experience of building airtight homes in countries in very cold climates, such as Canada, central Europe, parts of the USA and Scandinavia, provides insights into construction practices that may be increasingly adopted in the UK. However, direct transfer of knowledge is problematic and there is a dearth of information about indoor air quality in highly energy efficient structures. Requirements for research into the performance of highly energy efficient homes and the quality of the internal environment ventilation systems, and the impact on the health and wellbeing of occupants, are identified.

The review is based on an extensive literature review of over 100 references and publications, and includes appendices relating to the Code for Sustainable Homes, PassivHaus, Canadian R-2000TM homes, and the US EPA Indoor airPLUS specification.

ABOUT THE NHBC FOUNDATION AND THE ZERO CARBON HUB

The NHBC Foundation was established in 2006 by the NHBC in partnership with the BRE Trust. Its purpose is to deliver high-quality research and practical guidance to help the industry meet its considerable challenges.

Since its inception, the NHBC Foundation's work has focused primarily on the sustainability agenda and the challenges of the government's 2016 zero carbon homes target. Research has included a review of microgeneration and renewable energy techniques and the groundbreaking research on zero carbon and what it means to homeowners and housebuilders.

The NHBC Foundation is also involved in a programme of positive engagement with government, development agencies, academics and other key stakeholders, focusing on current and pressing issues relevant to the industry.

Further details on the latest output from the NHBC Foundation can be found at www.nhbcfoundation.org.

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Established in 2008, the Zero Carbon Hub supports and reports to the 2016 Taskforce which is chaired by the Housing Minister and the Executive Chairman of the Home Builders Federation. It is a public/private partnership established to take day-to-day operational responsibility for co-ordinating delivery of low and zero carbon new homes. This purpose will be fulfilled by monitoring, co-ordinating and guiding the zero carbon programme and engaging organisations active in low and zero carbon homes. To do this the Zero Carbon Hub is developing five integrated workstreams – energy efficiency, energy supply, examples and scale up, skills and training and consumer engagement.

For more information visit www.zerocarbonhub.org.

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GLOSSARY

ach	air changes per hour
CLG	Department for Communities and Local Government
CMHC	Canada Mortgage and Housing Corporation
CO	carbon monoxide
CO_2	carbon dioxide
COPD	chronic obstructive pulmonary disease
CSH	Code for Sustainable Homes
CVD	cardiovascular disease
EPA	Environmental Protection Agency
ETS	environmental tobacco smoke
GerES	German Environmental Survey
HHSRS	Housing, Health and Safety Rating Scheme
HPA	Health Protection Agency
HRV	heat recovery ventilator
HVAC	Heating, ventilation and air conditioning
IAQ	indoor air quality
IEQ	indoor environmental quality
MV	mechanical ventilation
MVHR	mechanical ventilation with heat recovery
MVOC	microbial volatile organic compound
NO_2	nitrogen dioxide
NOx	oxides of nitrogen
NZEH	Net Zero Energy Housing
OSB	oriented strand board
PAH	polycyclic aromatic hydrocarbons
PV	photovoltaic
RH	relative humidity
SBS	sick building syndrome
SEH	Survey of English Housing
SHGC	solar heat gain co-efficient
SHS	sick house syndrome
SVOC	semi-volatile organic compound
TVOC	total volatile organic compound
VOC	volatile organic compound
WHO	World Health Organization

EXECUTIVE SUMMARY

In line with its intention that all new homes in England will be zero carbon by 2016, the government is committed to progressive tightening of the energy efficiency aspects of the Building Regulations. Changes to the Building Regulations are complemented by the Code for Sustainable Homes which measures the sustainability of a new home against nine categories of sustainable design and construction.

Recent research by the NHBC Foundation (Davis and Harvey, 2008) has highlighted concerns of homeowners and builders about the possible adverse consequences on indoor air quality of the greater airtightness of the building envelope that is required to improve energy efficiency. Lack of air infiltration could lead to poor air quality since stale indoor air is not replaced at a sufficient rate by fresh outdoor air – with potential for any or all of pollutants build-up, high humidity and condensation (leading to mould growth), damage to structures and proliferation of house dust mites.

Because of its central role in determining the exposure of the population to air pollution, a case could be presented for more research into indoor air quality in homes. For the purposes of this review, however, the following main features of highly energy efficient homes are considered (together with their possible impact on air quality parameters relative to current Building Regulation requirement): increased airtightness, increased winter internal temperature, summer internal temperatures, mechanical ventilation, heat recovery aspect, materials for construction and ground contaminants.

In order to satisfy the energy use demands of the Code for Sustainable Homes in homes built to Code Level 4 and above, it is expected that mechanical ventilation with heat recovery will need to be applied in order to achieve an acceptable indoor climate, which represents something of a culture change in the UK. With widespread use of such mechanical ventilation with heat recovery systems comes the need for good understanding of their operation, performance and maintenance. Also, there is a possibility that householders would seek to counteract poor air quality or lack of the feel of ‘freshness’ by opening windows on a regular basis, thereby serving to offset the inherent benefits of a structure built to standards of high energy efficiency fitted with a continuously operating ventilation system.

The operation of mechanical ventilation systems in very well sealed dwellings during warm periods also raises questions about their potential effectiveness at removing heat and minimising overheating.

This review considers the current state of the art as regards airtight houses in the UK and elsewhere in the world with regard to the indoor environment they provide, and identifies requirements for further research in this area. The review starts with a summary of typical characteristics of Code Level 4 to 6 homes built under the Code for Sustainable Homes.

In sections 1 and 2, research in the UK, Europe and the rest of the world into indoor air quality and other relevant factors which may impact on occupant wellbeing, is reviewed. This is followed by a review of current research and state of the art concerning both ventilation performance in dwellings and of construction and ventilation provision in highly energy efficient homes – in all cases considering both the UK and elsewhere.

Using the literature and information gathered and summarised in the review, the authors present a summary of perceived research needs concerning the indoor environment in energy efficient homes and the ventilation systems required to maintain it within acceptable standards.

There is no published study of highly energy efficient homes in the UK that monitors the range of air quality and other factors that can affect occupant health and wellbeing. Of course, only a limited number of homes currently exist at Code Level 4 and above and the definition of Code

Level 6 is currently the subject of government consultation. However, it is notable that comprehensive studies of the indoor environment of UK homes are few.

Possibly more informative to our understanding of highly energy efficient homes are studies in other countries with experience of building airtight homes, particularly for very cold climates, such as in Canada, central Europe, parts of the USA and Scandinavia. Experience from other countries provides a useful insight into the likely construction practices that may be increasingly adopted in the UK. However, there are differences in climate, construction practice and the social and economic circumstances of occupants, and therefore direct transfer of knowledge is problematic. With regard to indoor air quality in particular there is a dearth of information relevant to highly energy efficient structures.

In conclusion, there appears to be an urgent need for research into the performance of highly energy efficient homes with respect to the quality of the internal environment ventilation systems used, and the impact on the health and wellbeing of occupants. Two broad but inter-related topics require investigation:

1. Performance of products and designs:
- Noise generated
- Ability to clean fans and ductwork
- Achievement of the required air supply
- Air filter efficiency
- Use of demand control ventilation
- Impact of chemical emissions from materials on indoor air quality.

2. Performance of Code Level 4 to 6 homes:
- Performance of systems at installation, during one year of use, and beyond.
- Evaluation of indoor air quality and ventilation in a representative sample of homes (temperature, relative humidity, volatile organic compounds, formaldehyde, carbon monoxide, nitrogen dioxide, particles, mites, bacteria, fungi, radon, ozone, semi-volatile organic compounds in dust, carbon dioxide and air exchange rate).

1 Introduction

Housing accounts for around 30% of the UK's total energy use and 27% of its carbon dioxide (CO_2) emissions. As part of policy to combat the effects of climate change the government intends that all new homes in England will be zero carbon by 2016, with a progressive tightening of the energy efficiency aspects of the Building Regulations in advance of that target date. The changes to the Building Regulations will be complemented by the Code for Sustainable Homes (CSH) which measures the sustainability of a new home against nine categories of sustainable design and construction.

Recent research by the NHBC Foundation has highlighted concerns of homeowners and builders about the possible adverse consequences on indoor air quality (IAQ) of the greater airtightness of the building envelope that is required to improve energy efficiency (Davis and Harvey, 2008). The lack of air infiltration could lead to poor air quality because stale indoor air is not replaced at a sufficient rate by fresh outdoor air. This would in turn result in a build-up of concentrations of pollutants in the indoor air that have been released by building materials, furnishings and consumer products, as well as people and their pets. Associated with this is the risk of high humidity and condensation, with the attendant risks of mould growth, damage to structures and proliferation of house dust mites.

In the case of homes built to Code Level 4 of the CSH and above, it is expected that, to achieve an acceptable indoor climate, while satisfying the demands of the CSH with respect to energy use, mechanical ventilation with heat recovery (MVHR) will be applied. There is a very real need to assess whether the MVHR products, currently on the market and being installed, are able to maintain good IAQ throughout the year in very airtight dwellings.

Moving from largely passive ventilation in most dwellings, to a 'sealed' unit relying on mechanical systems, is a large step change in terms of culture in the UK, and requires an understanding of the operation of the systems employed to ensure good performance. To facilitate this change, developers and ventilation system manufacturers must render their use intuitive and straightforward.

The operation of mechanical ventilation (MV) systems in very well sealed dwellings during warm periods raises questions about their potential effectiveness at removing heat and minimising overheating. Currently this is not effectively considered in the design or regulatory assessment of systems for dwellings. Evidence of overheating is currently largely anecdotal or based on dynamic thermal modelling predictions with little real data on the actual extent of the problem.

There is the very great possibility that householders would seek to counteract poor air quality or lack of the feel of 'freshness' by opening windows on a regular basis, and thereby serve to offset the inherent benefits of a structure built to standards of high energy efficiency fitted with a continuously operating ventilation system. This, and other occupant interventions (caused by concerns regarding noise and elevated energy costs, as well as air quality issues) could result in adverse air quality with consequent risk of condensation, mould growth, dust mite infestation and elevated volatile organic compound (VOC) concentrations – all of which could pose a health risk to occupants. This could be compounded by extensive use of composite and other polymeric materials, including those used to achieve high levels of insulation; such materials could provide a stronger source of chemical emissions than traditional materials.

This review considers the current state of the art as regards airtight houses in the UK and elsewhere in the world with regard to the indoor environment they provide, and identifies needs for further research.

2 Characteristics of Code for Sustainable Homes Level 4 to 6 homes

The CSH measures the sustainability of a new home against nine categories of sustainable design, rating the 'whole home' as a complete package. The CSH uses a 1 to 6 star rating system to communicate the overall sustainability performance of a new home. It sets minimum standards for energy and water use at each level and, within England, replaced the EcoHomes scheme, developed by BRE. On 27 February 2008 the government confirmed that rating against the CSH would be mandatory from 1 May 2008.

The CSH aims to provide valuable information to homebuyers, and to offer builders a tool with which to differentiate themselves in sustainability terms. There are two main documents describing the CSH: one sets out the assessment process and the performance standards required (CLG, 2008) and the second provides information on the detailed evidence required to meet the standards and sets out the assessment methodologies (CLG, 2008a). Code Level 1 is above current regulatory standards and higher code levels are increasingly stringent – with Code Level 4 representing current exemplary performance and Code Level 6 an aspirational level based on zero carbon emissions and high performance across all environmental categories.

The categories of environmental impact assessed are:

1. Energy and CO_2 emissions
2. Water
3. Materials
4. Surface water run-off
5. Waste
6. Pollution
7. Health and wellbeing
8. Management
9. Ecology.

None of these categories directly addresses IAQ. Under category 1 the sub-category 'Ene 2' (Building fabric) involves calculation of a heat loss parameter that includes the airtightness of the structure, thereby influencing the amount of air infiltration. 'Ene 4' concerns adequate secure space for drying of clothes and standards for ventilation of any such internal space and is aimed at reducing the risk of high humidity and condensation associated with that activity. Under category 7 credits are provided for good daylighting, sound insulation and provision of outdoor space. While the first two of these issues may benefit the quality of the indoor environment they do not impact upon IAQ. Category 8 concerns provision of guidance to understand and operate the home efficiently and through correct operation of ventilation and heating systems this should in practice benefit IAQ, although such benefits are difficult to quantify.

In an answer to a recent parliamentary question, it was reported by the Communities Minister that, by the end of February 2009, 39 developments had been certified post-construction under the CSH (six of these being at Levels 4–6), that 1082 had been certified at the design stage, and that over 170 000 had registered for the CSH. The Department for Communities and Local Government (CLG) has since informed the NHBC that these figures rose to 65 post-construction certificates, 1231 design stage certificates and over 191 000 registrations by the end of March 2009.

The definition of zero carbon homes is explored in a government consultation document published in December 2008 (CLG, 2008b). The proposed approach would consider net emissions of carbon (including that from appliances) over the course of a year. To meet the standard, homes should:

- be built with high levels of energy efficiency
- achieve at least a minimum level of carbon reductions through a combination of energy efficiency, onsite energy supply and/or (where relevant) directly connected low carbon or renewable heat
- choose from a range of (mainly offsite) solutions for tackling the remaining emissions.

The intention is for social housing to pave the way for zero carbon housing with homes funded under the National Affordable Housing Programme to be zero carbon and Code Level 6 by 2015 if the technology to achieve this cost effectively is available. As part of the definition of zero carbon homes seven broad aspects are identified by CLG:

i. technical feasibility

ii. economic and financial viability

iii. adaptability and flexibility

iv. relevant carbon reductions

v. a workable regulatory framework

vi. broader environmental considerations

vii. zero carbon homes as desirable and healthy homes.

Under point vii, the government considers that it would not be acceptable if zero carbon homes were less desirable or healthy than those built under current standards. Air quality is mentioned, albeit not strongly as a requirement as follows:

> 'the living environment should be attractive in terms of temperature (keeping cool as well as warm, taking into account future climate conditions), ventilation, air quality and noise'.

A companion document on assessing the impact of the proposed policy of zero carbon homes was also published by CLG in December 2008 (CLG, 2008c). There is recognition in the section on environmental impact of possible consequences for air quality (section 130). This paragraph refers to possible benefits such as fewer problems with pollen and other airborne allergens in the home. It also states that negative effects are also possible, but refers to planned revision of Part F of the Building Regulations which will look specifically at ventilation system requirements and IAQ issues to ensure that health standards are not undermined.

Expected changes to the Building Regulations in 2010, 2013 and 2016 for dwellings have been outlined in a forward look paper (CLG, 2007) and these equate to the energy performance standards in the CSH for Code Levels 3, 4 and 6 respectively. A number of illustrative designs are described to meet the proposed new requirements that include more airtight building envelopes and options for MVHR and natural ventilation. In the section on implications, it states that advanced standards of airtightness will make a significant contribution to the 2010 and 2013 standards, particularly when coupled with high performance MV systems. It notes that Part F will need to be kept under review in parallel with developments in Part L (Conservation of fuel and power) to ensure that CO_2 reductions are not achieved at the price of unsatisfactory IAQ.

Osmani and Reilly (2009) surveyed opinion of UK housebuilders about the feasibility of constructing zero carbon homes by 2016. Numerous legislative, cultural, financial and technical barriers are identified and the need for the urgent implementation of a realistic strategy that is adopted across the supply chain. They note that the CSH exceeds other international housing standards such as the R-2000TM Program in Canada and the PassivHaus in Germany, as all domestic energy used must be generated by renewable sources to achieve Code Level 6. The PassivHaus standard sets a permissible energy use of 15 k Wh/m^{2}y for space cooling and heating but does not specify the source of the energy used.

3 Indoor air quality and occupant wellbeing

3.1 Introduction

Appropriate IAQ can be defined as the absence of air contaminants which may impair the comfort or health of building occupants (Rousseau, 2003). Jacobs et al. (2007) define indoor air pollution as chemical, physical or biological contaminants in the breathable air inside a habitable structure or conveyance, including workplaces, schools, offices, homes and vehicles. It includes the following;

- combustion by products such as carbon monoxide (CO) and nitrogen dioxide (NO_2)
- ozone
- allergens including mould spores
- building materials and furnishings
- cleaning products, personal care products, air fresheners and pesticides used indoors
- tobacco smoking, hobbies, cooking, and other occupant activities as well as dry cleaned clothes
- bioeffluents
- soil gas intrusion including radon.

Exposure to pollutants may cause a variety of effects ranging in severity from perception of unwanted odours to cancer (ECA, 2003). Examples of health effects are dispersal of airborne infectious disease, micro-organisms in air humidifiers causing pneumonia and humidifier fever, mould increasing risk of allergy, and an increased risk of lung cancer through exposure to environmental tobacco smoke (ETS) and radon. Sensory effects include:

- adverse health effects on sensory systems
- adverse perceptions such as annoyance reactions and triggering of hypersensitivity reactions
- sensory warnings of harmful factors such as irritation due to formaldehyde.

Interactions of processes determining heat, moisture and air movement in buildings impact upon air quality and therefore need to be understood and taken into account when designing buildings. Some key principles summarised from Rousseau (2003) are as follows:

- To reduce operating costs, increase comfort and prevent interior condensation, levels of insulation of walls, floors and ceilings are increased. However, this will increase the likelihood of condensation forming inside wall and ceiling cavities in the heating season with associated risk of rot, mould growth and reduced insulation performance.
- To reduce heat losses by air leakage a continuous air barrier is incorporated in the insulated walls and this can have the benefit of reducing entry of outdoor air pollutants. However, moisture and pollutants generated indoors will thereby remain in the building longer unless removed by suitable ventilation.
- Sources of pollutants and moisture are controlled by careful selection of products such as building materials, furnishings and heating appliances. Remaining pollutants are normally removed and diluted by a continuously operated, mechanical distributed ventilation system. However, this mechanical system increases energy consumption and therefore a heat recovery ventilator (HRV) may be applied.

3.2 Sources of indoor pollution

There is an extensive scientific literature on the sources of indoor pollution including a number of reviews (Bruinen de Bruin et al., 2005; Pluschke, 2004; Crump et al., 2002; Crump, 1997; Fernandes et al., 2009; Maroni et al., 1995; Morawska and Salthammer, 2003; and Salthammer, 1999). Table 1 provides a summary of the main sources and types of pollutant.

TABLE 1

Sources and types of indoor air pollution

Source	**Main pollutants**
Outdoor air	SO_2, NOx, ozone, particulates, biological particulates, benzene
Combustion of fuel	CO, NOx, VOCs, particulates
Tobacco smoke	CO, VOCs, particulates
People	CO_2, organic compounds
Building materials	VOCs, formaldehyde, radon, fibres, other particulates, ammonia
Consumer products	VOCs, formaldehyde, pesticides
Furnishings	VOCs, formaldehyde
Office equipment, including HVAC	VOCs, ozone, particulates
Bacteria and fungi	VOCs, biological particulates
Contaminated land	Methane, VOCs, contaminated dusts eg metals
Ground	Radon, moisture
Washing and cleaning	Moisture
Animals (eg mites, cats)	Allergens

VOCs are emitted over periods of weeks or years from construction and furnishing products and have the potential to cause poor air quality. There is a growing interest in release of VOCs from consumer products including electrical goods such as computers and printers as well as cleaning products and air fresheners. ETS contains a complex mixture of organic compounds and while smoking is banned in the workplace and public buildings in the UK, it remains a significant source of airborne pollution in many homes.

Formaldehyde is a very volatile organic compound (VVOC) that has been widely studied because of its release from a range of building and consumer products. Semi-volatile organic compounds (SVOCs) have a relatively low vapour pressure and therefore tend to occur at lower concentrations in indoor air than the more volatile of VOCs. They include plasticisers used in polymeric materials such as vinyl floorings and paints, pesticides such as DDT and pentachlorophenol, and polycyclic aromatic hydrocarbons (PAHs) produced during fuel combustion and present in coal tar and in tobacco smoke. Microbial volatile organic compounds (MVOCs) are volatile compounds released as the result of the metabolism of fungi: they include ethanol and a range of higher alcohols and ketones.

The principal sources of inorganic pollutant gases in indoor air are the outdoor air, combustion of fuel, and respiration by people and animals. The main sources of combustion gases in buildings are related to space heating (especially open-flued or unflued gas and paraffin heaters), water heating and cooking. Other sources include tobacco smoke and vehicles (in attached garages or close to ventilation air intakes).

CO_2 is a natural constituent of air and only in exceptional circumstances is it present in sufficient amounts to be a danger to health. It can be present in buildings as a result of respiration of people and animals, as a product of combustion and as a component of soil gas. It is widely used as an indicator of ventilation rate and, effectively, as a proxy for body odour. CO is a colourless, odourless gas, produced by the incomplete combustion of most fuels. Incomplete combustion can occur, eg when inadequate ventilation to an appliance results in depletion of the oxygen content of the air at the point of combustion. The major indoor sources of nitrogen oxides (NO_x, including nitrogen dioxide NO_2), are gas-fuelled cookers, fires, water heaters and space heaters, and oil-fired space heaters. Sulphur dioxide (SO_2) is produced by burning sulphur-containing fuels such as coal and oil.

Ozone is primarily a pollutant of ambient air produced by photochemical reaction. It undergoes reaction indoors with surfaces and airborne pollutants to produce new organic compounds and particles. Water vapour is produced by people during activities such as cooking, cleaning and washing, as well as through normal respiration. The amount of water vapour in the air has direct effects on health and comfort and is also important in relation to the occurrence of biological pollutants.

Particles in the air may arise from a wide variety of sources, both natural and related to human activity. Particles generated indoors are mainly from mechanical processes such as cleaning and physical activity by occupants. Particles in the sub-micron ranges are generated during combustion as well as from secondary processes such as gas to particle conversion and nucleation or photo-chemical processes. The main indoor sources of these sub-micron particles include smoking and cooking and the operation of gas burners, ovens and electric toasters. Fibres are a particular type of particles and the use of asbestos in buildings has been an important route of worker and population exposure.

There are four main types of particles of biological origin that are significant for human health in most buildings: faecal pellets of the house dust mite, fungal particles, bacteria and pollen. Mite levels are often highest during the late summer/early autumn as they reproduce rapidly in conditions of high ambient humidity and warm temperatures. Other allergenic particles can also be present in the indoor air, eg from domestic animals (eg cats, dogs, birds) and pests (eg cockroaches). Most fungi produce microscopic spores which are released into the air and serve to spread the fungus. In addition, microscopic hyphal fragments or cells of surface-growing fungi such as moulds or yeasts may become detached and become airborne. Pathogenic (disease-causing) bacteria are present in the indoor air, originating from people and water spray, and potentially other sources such as food and animals. A wide variety of species of non-pathogenic bacteria also occur naturally in buildings. Pollen is mainly entrained from the outdoors, with tree pollen predominating during the early spring and the grass pollen season occurring during late spring and early summer.

Radon is a naturally occurring radioactive gas that can enter buildings from the ground and the amount of ingress depends upon a number of factors including local geology, the type of foundation/floor, the positioning of service pipework and internal ventilation levels. Measures such as installation of gas-proof membranes in the foundations of new buildings can significantly reduce levels of radon gas (HPA, 2008).

Methane and associated gases, including CO_2, hydrogen and a wide range of organic compounds, are produced in landfill sites when micro-organisms break down organic material such as vegetable matter, wood, paper, etc. Chemical vapours may also be present in the ground through pollution of soil and groundwater resulting from industrial sites, waste disposal and accidental chemical spillage and leakage. Buildings may be influenced by these vapours if constructed on contaminated land that has not been adequately remediated, or because of the movement of vapours and contaminated groundwater from neighbouring sites (Crump, 2004).

3.3 Studies of relationships between indoor air quality and health

There are a wide range of reviews and specific studies on relationships between exposure to indoor pollutants and health effects. This section refers only to some quite recent publications. The European Commission Scientific Committee on Health and Environmental Risks reviewed current approaches to risk assessment of indoor air pollutants (SCHER, 2007). It concluded that indoor air may contain over 900 chemicals, particles and biological materials with potential health effects. They note that concentrations of pollutants are usually higher indoors than outdoors and that people spend most of their time indoors. They recommend a focus on evaluating sources of pollutants and seeking to reduce exposures because of the difficulties of regulating the diverse range of indoor air scenarios. They identify a need for more research including work on exposure, reactions between pollutants, combined and mixture effects, causative factors to explain the link between dampness and health and development of health-based guideline values.

CLG (2008d) summarises evidence for the impact of buildings on human health and safety and identifies 33 hazards including the following associated with IAQ:

- biocides
- carbon monoxide
- cockroaches
- environmental tobacco smoke
- explosions in buildings
- fungal growth
- house dust mites
- hygrothermal conditions
- land contamination including landfill gas
- lead
- particles and fibres
- radon
- oxides of nitrogen
- volatile organic compounds
- sulphur dioxide.

In addition other factors relating to the indoor environment are identified including noise, lighting, slips, trips and falls, sources of infection and electromagnetic fields.

Carrer et al. (2009) reviewed the main studies of indoor air-related health effects and prioritised the following diseases as being caused or aggravated by poor IAQ:

- allergic and asthma symptoms
- lung cancer
- chronic obstructive pulmonary disease (COPD)

- airborne respiratory infections
- cardiovascular disease (CVD)
- odour and irritation (sick building syndrome symptoms).

Allergic and asthma symptoms are increasing throughout Europe affecting between 3 to 8% of the adult population with higher prevalence in infants (29–32% in Ireland and UK in 1995/96). The cause of allergic diseases is considered to be a complex interaction between genetic and environmental factors and asthmatic patients are sensitive to allergens present in the indoor environment and are often hyperactive to a number of gases and particles. The following may have a role in the development of allergy and asthma:

- Microbial agents (endotoxin of Gram negative bacteria, fungal spores and fragments, bacterial cells, spores and fragments, microbial metabolites and allergens including house dust mites, pet allergens and fungal allergens).
- Chemicals (formaldehyde, aromatic and aliphatic chemicals, phthalates or plastic materials, products of indoor chemistry involving reactions of ozone and terpenes).

Lung cancer is the most common cause of death from cancer in the EU (about 20% of all cases). Most are due to active smoking, but it is estimated that 9% are due to radon exposure in the home and 0.5% in males and 4.6% in females are due to exposure to ETS. There is some evidence of risk due to combustion particles including PM2.5 (particulates with an aerodynamic diameter below 2.5 µm) in ambient air, and due to diesel exhaust and indoor cooking oil and coal burning.

COPD is a chronic respiratory disorder that is usually progressive and associated with an inflammatory response of the lungs to noxious particles or gases. It is estimated that the prevalence of clinically relevant COPD in Europe is between 4 and 10% of the adult population. About 70% of COPD related mortality is attributed to cigarette smoking. Other risk factors identified are ETS, biomass combustion fumes, particles in ambient air and long-term exposure to mould/dampness.

Airborne infectious diseases include Legionnaire’s disease, tuberculosis, influenza and SARS (severe acute respiratory syndrome). Reservoirs in aquatic systems such as cooling towers, evaporative condensers and humidifiers have been the source of airborne agents in outbreaks of Legionella and pneumonia. Symptoms of these diseases can be aggravated by exposure to ETS and combustion particles.

CVD is the leading cause of death in industrialised countries accounting for 42% of deaths in the EU. Causes include exposure to ETS, particles, CO and other gaseous pollutants (NO_2 in particular).

Sick building syndrome (SBS) describes cases where building occupants experience acute symptoms and discomfort that are apparently linked to the time spent in the building, but for which no specific illness can be assigned. Symptoms include respiratory complaints, irritation and fatigue. Sensory perception of odours leads to a perception of poor air quality and consequently stress initiated behavioural responses (eg opening windows). Other environmental stressors such as noise, vibration, crowding, ergonomic stressors and inadequate lighting can produce symptoms similar to those caused by poor air quality. The negative effects can reduce productivity in offices and learning ability in schools. In buildings without complaints of poor IAQ the prevalence of symptoms is often close to zero and normally found in less than 30% of occupants. In affected buildings prevalence may be between 50 and 100%.

Jacobs et al. (2007) review knowledge of the links between health and the quality of the indoor environment of homes, and policies in the USA, to address these risks to health. Indoor air pollution is one of the top four health risks identified by the US Environmental Protection Agency (EPA). On average people spend 90% of their time indoors where pollutants may be two to five times higher than outside and occasionally 100 times higher. This pollution is estimated to cause thousands of cancer deaths and hundreds of thousands of cases of respiratory health problems each year. Millions of children have experienced elevated blood levels of contaminants from exposure to indoor pollutants. Other effects include irritation, and more subtle neurotoxicological, behavioural and other adverse effects. The associated economic costs are considerable, the EPA estimating that net avoidable costs in 2001 alone were likely to be between $150 billion and $200 billion.

Mitchell et al. (2007) reviewed current knowledge on health effects and indoor environmental quality and suggest a particular need for research on interactions of multiple exposures, risks to particular vulnerable groups (eg children), benefits of interventions and trade-offs for ventilation and energy efficiency, and better measurements of dose, particularly for biological agents.

While smoking is the greatest risk factor for lung cancer, causing more than 30 000 cases each year, radon is the second most common cause in the UK and it is estimated that this causes 2000 cases per year (HPA, 2008). To protect against this risk, the Health Protection Agency (HPA) has recommended that all new properties should incorporate methods to reduce internal levels of radon. They comment that the low ventilation rates common in modern buildings for energy conservation reasons can encourage the build-up of radon gas concentrations indoors.

Mendel (2007) reviewed 21 research studies that have associated residential chemical emissions from indoor materials and activities with risk of asthma, allergies and pulmonary infections. Risk factors identified most frequently included formaldehyde or particleboard, phthalates or plastic materials, and recent painting. Others such as aromatic and aliphatic chemical compounds were suggestive. Elevated risks were also reported for renovation and cleaning materials, new furniture and carpets or textile wallpaper. It is concluded that while these risk factors may only be indicators of truly causal factors, the overall evidence suggests a new class of residential risk factors for adverse respiratory effects that is ubiquitous in modern residences. If the associations are proved to be causal, Mendel considers it would mean that there is a large-scale occurrence of adverse respiratory and allergic effects in infants and children that is preventable and related to modern residential building materials and coatings, and possibly exacerbated by decreased ventilation.

Fisk et al. (2007) undertook a meta-analysis of 33 studies investigating an association between occurrence of indoor dampness and mould with adverse health effects. This found building dampness and mould to be associated with an approximately 30 to 50% increase in a variety of respiratory and asthma-related health outcomes. The studies included those recording visible dampness and or mould, or mould odour, by investigators or the occupants themselves.

The evidence for the effects of ventilation on health, comfort and productivity in non-industrial indoor environments was reviewed by a multidisciplinary group of scientists (Wargockj et al., 2002). They concluded that ventilation is strongly associated with comfort (perceived air quality) and health (SBS symptoms, inflammation, infections, asthma, allergy, short-term sick leave). Ventilation rates above 0.5 ach in homes were found to reduce infestation of house dust mites in Nordic countries.

Venn et al. (2003) investigated the relationship between exposure to some indoor air pollutants and the occurrence of childhood wheezing illness in a study of 410 homes in Nottingham. They reported indoor concentrations of total volatile organic compounds (TVOCs), some individual VOCs, formaldehyde, and NO_2, took measurements of surface dampness and recorded presence of mould. Visible mould was only identified in 11 homes but was significantly associated with an increased risk of wheezing illness. The risk of wheezing was significantly increased by dampness. Among the 193 cases with persistent wheezing, formaldehyde and damp were associated with more frequent nocturnal symptoms.

Osman et al. (2007) measured concentrations of particulates (PM2.5) and NOx in air and endotoxins in house dust in homes of 148 patients in Scotland suffering from severe COPD. PM2.5 was significantly higher in smoking households and these levels were associated with the poorer health status of the patients.

Niven et al. (1999) reviewed studies that had sought to manipulate the internal environmental conditions to control house dust mites. Reducing humidity appeared to provide some benefits in Scandinavian homes but studies of installing MVHR in British homes had not proved it effective. The researchers fitted MVHR units with dehumidification in homes of 10 asthmatics and monitored dust mite allergen in dust over a 15 month period. They also monitored 10 control homes not fitted with MVHR. Average humidity in the bedroom was lower in the MVHR homes but there was no significant reduction in allergen levels.

There is little available information about IAQ in Code Level 4 to 6 homes in the UK. Yu and Crump (2007) argued for IAQ criteria to be included as part of the health and wellbeing requirements under the CSH. This would involve an assessment of materials used at the design stage, establishment of the adequacy of a management plan for IAQ, and compliance testing of IAQ parameters in the completed building. In the absence of data for CSH compliant homes consideration of possible IAQ issues needs to be drawn from experience of studies in existing homes and studies of energy efficient homes in other countries. A comprehensive review of the large number of worldwide studies of IAQ would not be feasible and therefore this review is limited to major surveys and those particularly addressing new homes.

3.4 National studies of indoor air quality in homes

UK

There have been no published studies of IAQ in highly energy efficient homes. The BRE survey of IAQ in homes in England undertaken in 1997 to 1999 measured a range of pollutants in over 800 randomly selected and normally occupied homes (Coward et al., 2001). It involved the measurement of NO_2, CO, formaldehyde and VOC concentrations using diffusive samplers and recording of information about household characteristics and activities.

The study used the Survey of English Housing (SEH) to select homes and to invite householders to participate in the study. The SEH is a survey undertaken by government to provide data on the housing stock and involves visits by interviewers to 20 000 randomly selected homes each year. The characteristics of the 876 homes completing the study was compared with that of the 20 000 homes (Coward et al., 2001) and shown to be representative with some small biases for particular population groups, such as the proportion of participants aged over 75 years (8.5% in the BRE IAQ survey and 12.5% in the SEH).

In about 5% of homes the TVOC concentration exceeded 1000 µg m^{-3} and the geometric mean value for all homes was 210 µg m^{-3}. Formaldehyde levels exceeded the recommended World Health Organization (WHO) guideline of 100 µg m^{-3} in 0.7% of the homes. There were seasonal differences in the TVOC concentration, with highest mean concentrations occurring in autumn. Concentrations were higher where painting had occurred in the home during the sampling period or in the previous 4 weeks, and homes with an integral garage exhibited higher levels than those with a detached garage or no garage. After adjusting for homes that had painting undertaken, concentrations of TVOC were higher in newer homes and in bedsits and flats than in other types of dwellings. Formaldehyde varied significantly with building age, newer homes having higher concentrations. The presence of particleboard flooring was associated with higher formaldehyde concentrations. Benzene concentrations were higher in urban areas, in homes with smokers, and in those homes with attached or integral garages.

NO_2 concentrations were significantly higher in kitchens than in bedrooms because many homes had cooking-related sources in the kitchen. CO levels were higher in autumn and winter than in spring and summer, and the highest levels in kitchens were associated with the presence of a gas oven for cooking.

The national survey determined average concentrations of pollutants over periods of days to weeks and did not consider short-term peak concentrations which are also a potential health concern. To address this issue, at least for CO and NO_2, a separate study of 73 gas-cooking homes was undertaken using continuous monitoring methods (Ross and Wilde, 1999). This study found that 13% of the homes during summer, and 18% of the homes during winter, had CO levels that exceeded the WHO 1 hour guideline value (WHO, 2000). The sample mean of maximum hourly-averaged NO_2 levels in the kitchen was 310 µg m^{-3} in the summer and 424 µg m^{-3} in the winter.

One important determiner of IAQ not investigated was the rate of ventilation; this was because of the technical difficulties and costs of such measurements. A further study of 37 homes in England, built since 1995 and undertaken in 2002, did involve simultaneous measurements of air quality and rates of ventilation (Dimitroulopoulou et al., 2005). All homes in the study had central heating with radiators and were double glazed with trickle ventilators in the window units to provide background ventilation.

Measurements of airtightness of the homes with windows and doors closed, expressed as ach at 50 Pa, were undertaken using a fan pressurisation technique prior to the monitoring of indoor pollutants. VOCs, NO_2, CO and formaldehyde were measured using diffusive samplers with an exposure period of three days to 2 weeks, depending on the pollutant. PM10 was measured using a pumped gravimetric method with a sampling period of 24 hours. Information was collected about the characteristics of the properties and the activities of occupants using questionnaires. Concurrent with the pollution measurements, a perfluorocarbon tracer method was used to determine the mean rate of air exchange of the indoor air with outside air for the 2 week period.

The results from the measurements were statistically analysed, based on data from questionnaires, including house characteristics and occupant activity diaries.

In winter, 68% of homes had a whole house ventilation rate below the minimum design value of 0.5 ach, which according to BRE research is necessary to avoid condensation. In summer, 30% of homes had a whole house ventilation rate below 0.5 ach. Some relationships between the amount of ventilation and the concentration of some pollutants were found as well as correlation between particular sources and pollution, such as the presence of a gas cooker and the concentration of NO_2.

A study of IAQ and ventilation in a sample of 20 homes in England built according to the 2006 version of the Building Regulations has been commissioned by CLG (Department for Communities and Local Government) and further details are provided in Appendix B.

France

Ramlho et al. (2006) describes the French permanent survey on IAQ involving field measurement campaigns in different indoor environments. During 2003 to 2005, target indoor pollutants were determined in 567 dwellings selected at random to be representative of the 24 million homes in France. The target pollutants were CO (indoor and exhaled concentration), 20 VOCs, allergens (dog, cat, dust mite), radon and gamma radiation, and particulate matter (PM10, PM2.5). Comfort parameters were also measured: relative humidity (RH), temperature, CO_2, exhaust airflow rate. Questionnaires recorded information about occupants including their allergic and respiratory symptoms, and house characteristics. Activity diaries were also kept by occupants in the study. Results of a pilot study in 90 dwellings were reported by Kirchner et al. (2003) who found VOC levels for many compounds significantly higher indoors than outside.

Canada

Canada Mortgage and Housing Corporation (CMHC) considers indoor pollution as posing one of the most serious health risks, noting work in the USA that estimates that it causes thousands of cancer deaths and hundreds of thousands of respiratory health problems each year (CMHC, 2002). Recognising the lack of clear government structures or national strategies, CMHC initiated the ‘Healthy Indoors’ programme to create a strategy for creating and maintaining healthier buildings in Canada between 2002 and 2020. Among the five main goals of the programme are to foster the design of healthier new and renovated buildings and to create and use healthy products, such as those that have low emission of pollutants to the indoor environment.

NRC-IRC (2008) refers to increasing concerns about the effectiveness of MV systems to provide acceptable IAQ and large gaps in knowledge about the correlation between IAQ and the health of occupants. This has led to a new study of 100 homes occupied by families with asthmatic children in Quebec. Over a three year period modifications will be made to the ventilation and air distribution systems to improve IAQ and a follow-up study will be undertaken to assess any changes in IAQ and health. In preparation, a new test facility will be applied to optimise technologies such as heat recovery ventilation systems. This indoor air research facility allows a range of house designs to be studied and enables variation in airtightness, room size layout, types of heating and air conditioning systems, and HRVs to be applied and evaluated.

Prowskiw G (1992) monitored air quality in 20 detached bungalows of which 16 were constructed to the R-2000TM standard and four to conventional energy conservation standards. All contained some type of MV system ranging from small capacity bathroom exhaust fans to HRVs that were designed to run continuously and supply fresh air to all areas of the dwelling. Monitoring was undertaken over a three year period (March 1986 to March 1989) and involved regular measurement of concentrations of formaldehyde, radon, particulates, NO_2, CO_2, and RH, as well as total air change rates. The concentrations of pollutants were compared to residential exposure guidelines established by the Federal-Province Advisory Committee on Environmental and Occupational Health (1989):

- formaldehyde: 0.05 ppm target, 0.10 ppm action level
- radon: action if annual average exceeds 800 Becquerels m^{-3}
- particulate (PM2.5): long-term value of 40 $\mu g\ m^{-3}$
- NO_2: long-term value of 0.05 ppm
- CO_2: long-term value of 3500 ppm
- Relative humidity: 30 to 80% in summer, 30 to 55% in winter. Also recommended to be at 40 to 50% to minimise upper respiratory infections.

For formaldehyde the action level was readily achieved in R-2000TM homes, but the target was not reached consistently. Homes not operated according to R-2000TM ventilation guidelines had concentrations (mean 0.089 ppm) higher than homes in compliance (0.047 ppm). Particulates were higher in homes with smokers. NO_2, CO_2, radon and RH were within guideline values except for singular high readings.

Homeowner intervention with the MV systems was found to be a common occurrence resulting in utilisation rates lower than expected. The speed controls were adjusted or power to the unit disconnected. Homeowners explain why they do not use the MV systems on a continuous basis because of concerns about wasted energy, noise and discomfort caused by cold draughts.

Leech et al. (2004) undertook a telephone administered questionnaire survey of general and respiratory health of occupants of R-2000TM energy efficient homes and a control group residing in new homes in the same area of Canada. The aim was to compare the change in health status of the two groups during the year before occupancy, with that of one year after occupancy. The primary criterion for R-2000TM certification is a tight building envelope with MV by an HRV. A further mandatory requirement is the use of materials with less potential for volatile emission to the indoor air. The survey found that 10% of the R-2000TM residents did not realise they had an HRV. Only 76% operated it throughout the winter and 58% throughout the summer. Symptom scores for throat irritation, cough, fatigue and irritability improved significantly in the R-2000TM homes compared with the control home occupants – further work is required to investigate the link to any improvements in IAQ.

USA

Weschler (2008) reviewed knowledge about changes in IAQ in buildings in the USA since the 1950s to the present day. There is a lack of data particularly in buildings before the 1980s and therefore a consideration of changes in sources is used to infer likely changes in occupant exposure. While the observations are applicable to all buildings and not just high energy homes, some highlighting of the impact of changes in building materials, ventilation, consumer products, time spent indoors, outdoor air quality and occupant behaviour are a useful illustration of the interaction of social, economic and technical developments on IAQ and thereby exposure to pollutants.

The changes highlighted are the use of composite wood, synthetic carpets, polymeric flooring, foam cushioning, plastic items and scented cleaning agents as well as the growth in the use of appliances (eg TVs, computers, washers/dryers) in homes. This has resulted in changes to the types and amounts of the emissions of pollutants which has been accompanied by changes in building operations, particularly reduced ventilation. Some pollutants have declined through improvements to outdoor air quality and replacement of some toxic chemicals in products (eg benzene, asbestos). Some indoor pollutants such as phthalate ester plasticisers, brominated flame retardants, non-ionic surfactants, and coalescing solvents were not present in indoor environments in the 1950s; studies have demonstrated current occupant exposure by analysis of blood and urine. Weschler (2008) recommends that public exposure to pollutants is strongly influenced by the indoor environment and that monitoring networks should be established to understand the changes and the impacts of modifications to buildings, the products used in them and people’s behaviour (eg methods of cooking, smoking).

Angell et al. (2005) reviewed studies of air quality, ventilation and building-related health effects to identify priorities for further research in the USA. They refer to particular studies of effects of combustion appliances, integral garages and clothes dryers on IAQ and studies of personal exposure. They identify a critical need for a national residential building assessment and survey evaluation characterising residential IAQ across climatic regions modelled on the US 'BASE' study of commercial buildings that investigated IAQ.

Germany

Becker et al. (2007) summarise the German Environmental Survey (GerES) which is a nationwide population study that has been repeatedly carried out since the mid-1990s. The surveys aim to determine the exposure of the German population to environmental pollutants and involve biomonitoring, monitoring of the domestic environment, questionnaire investigations and measurements of noise.

The most recent survey (GerES IV) focussed on children and involved 1790 randomly selected 3 to 14 year olds – the domestic environment of 600 of these children was monitored. VOCs in air were determined as well as phthalates in house dust. Concentrations were compared with previous surveys and there was evidence for a decline in benzene and toluene concentrations. A significant correlation was found between di-n-butylphthalate in house dust and the presence of the metabolite monobutylphthalate in urine.

Maier et al. (2009) discuss the difficulties of modelling the interaction of heat consumption, comfort parameters and IAQ at the design stage because of the influence of the behaviour of occupants on building performance. They undertook a study of 22 identical houses with timber framed construction in Germany where four different ventilation systems had been installed; natural, ventilation system with air heating, MVHR and MV with single ventilators. They measured CO_2, temperature, RH, energy consumption, window opening, MV use and perceived thermal comfort over a two year period. MVHR demonstrated a 10 to 30% lower energy consumption than the other strategies. CO_2 concentrations were about 40 to 50% lower than those found with natural ventilation. Installation costs were higher for the MVHR system. Perceived air quality and comfort was good or very good with no differences between the four system types. In all cases occupants adapted their environment by opening windows and there was a strong correlation between time of opening windows and the CO_2 concentration. For MV homes, occupants modified the indoor environment by opening windows rather than modifying ventilation airflows. The study showed a strong effect of occupant behaviour on the interactions of energy use, comfort, IAQ and ventilation and plan to investigate further these relationships over smaller timescales (periods of one to two days).

Sweden

Bornehag and Stridh (2000) determined VOC levels in 178 randomly selected residential buildings in Sweden. About 120 single VOCs were identified and of these 27 had a mean concentration above 10 $\mu g\ m^{-3}$. The mean TVOC concentration was 350 $\mu g\ m^{-3}$ and that for formaldehyde was 12 $\mu g\ m^{-3}$.

Engvall et al. (2006) undertook a questionnaire study on the indoor environment and occupant health of residents in Stockholm comparing results for studies undertaken in 1991/92 with results for a repeat survey in 2005. The 2005 study focussed on homes built after the 1990s and found an increase in the proportion of complaints about thermal comfort as well as the proportion reporting SBS symptoms. For example, those reporting fatigue increased from 24 to 29% and eye symptoms increased from 8 to 13%.

Finland

Tuomainen et al. (2001) describe the classification of indoor climate, construction and finishing materials that gives target and design values for thermal conditions, odour intensity, noise levels, ventilation and IAQ in new buildings. It includes emission rates for building and finishing materials and recommends maximum surface area use of materials based on the emission characteristics. There are also three classes of IAQ: S1, S2 and S3 with target values for formaldehyde, TVOC and ammonia concentrations as well as temperature, humidity and air velocity. The authors investigated

IAQ in two blocks of flats, one constructed according to the recommended classification and one using more conventional building technology. After completion, TVOC concentrations were about 10 times higher in the control building. The S1 target values for temperature, RH, CO_2, formaldehyde and total suspended particles were achieved before occupancy and those for CO, TVOC and ammonia were reached within five months. The S1 target for odour was not achieved in the allotted time period. The authors conclude that IAQ was better in the flat built to the classification system than in the control building, the largest measured differences being the TVOC and ammonia levels, and that the system is a useful tool for the design and construction process.

A further study of eight residences constructed with low-emitting materials according to the Finnish classification found that target values of air pollutants were not generally reached in newly finished buildings (Jarnstrom et al., 2006). Lowest concentrations were achieved in buildings with MV and exhaust systems. Formaldehyde target values were achieved, TVOC generally met the S2/S3 class within 6 months, but ammonia remained above the S3 limit for 12 months. Air exchange rates were between 0.7 and 1.5 ach and these are above the minimum requirement of 0.5 ach. There was a rapid decline in VOC concentrations over the first 6 months. It is suggested that there is a need to further develop the Finnish classification particularly with respect to ammonia.

Palonen et al. (2008) assessed thermal comfort, perceived air quality and ventilation in 102 single family homes in Finland built since 1980. The study group included homes with passive stack ventilation, mechanical exhaust ventilation and mechanical supply and exhaust ventilation with heat recovery. Air change rates were measured in 74 homes over a 3 week period using a passive tracer gas technique. The most common indoor climate related problem was dustiness of surfaces (36% of houses). Stuffy air was a problem in 12%, insufficient ventilation during summer and ventilation noise were the most common problems related to the ventilation system. One third of homes were considered to be free from indoor climate problems but 20% had at least three problems. Measured air change rates were generally low compared with Finnish building regulation requirements of 0.5 ach, with average values of 0.30 ach for passive stack ventilation, 0.34 ach for mechanical exhaust and 0.41 ach for mechanical supply and exhaust ventilation.

Czech Republic

Urban et al. (2006) describe an investigation of the first low energy building constructed in the Czech Republic. It is a two-floored building with nine apartments served by MVHR. The study involved a questionnaire survey of occupants and evaluation of filters removed from the HVAC. Analysis of the filters did not reveal unexpected occurrences of fungi, pollen and bacteria. The questionnaire study identified a problem with a lack of information for users about the functioning of the heating, ventilation and air conditioning (HVAC) unit, the effect of its use and the purpose of the forced ventilation. The mechanically ventilated buildings were generally perceived as unhealthier and less comfortable for the user. There were reports of smell diffusion between apartments from the kitchen, a high level of noise from the HVAC and fungi were a problem in some apartments.

Japan

Yoshino et al. (2006) report that indoor air pollution by chemical substances is a serious problem in Japan and that such pollution is associated with sick house syndrome (SHS). They investigated 60 houses where occupants were suspected of suffering symptoms caused by indoor pollution. Concentrations of VOCs and formaldehyde as well as air exchange rates (in some) and airtightness were measured. Only 36% of 14 homes met the 0.5 ach required in the Building Standard Law, others being below this value. The concentration of formaldehyde, toluene, ethylbenzene, xylene, p-dichlorobenzene and TVOC was significantly higher in SHS homes. Concentrations were higher in new homes or following refurbishment, in those with high airtightness and low air change rate, and where there was new furniture or moth crystals were used.

Saijo et al. (2004) approached occupants of 564 dwellings in the Sapporo region of Japan with a questionnaire survey about health problems and allergies. The houses had been built or refurbished in the previous few years. One hundred and ninety one households gave permission for measurements and of these 67 complained of symptoms and 124 did not report symptoms. Women exhibited more symptoms than men, and they spent more time in the home. Levels of

VOCs and aldehydes were measured in a total of 96 dwellings drawn from the two groups. Concentrations of some individual VOCs (toluene, butyl acetate, ethylbenzene, xylene, alpha-pinene, nonanal, p-dichloro-benzene) and the sum of concentrations of identified VOCs were significantly related to symptoms of residents. There was no relationship between symptoms and formaldehyde and acetaldehyde concentrations. Dampness (condensation on window panes and/or walls and mould growth) was significantly related to symptoms and the risk was found to be higher where the number of signs of dampness increased.

Takeda et al. (2009) investigated health symptoms of 343 residents in 104 newly built detached houses at Hokaido. SHS symptoms were identified in 21.6% of dwellings. Measurements of aldehydes, VOCs, airborne fungi, and dust mite allergen were undertaken in the main living room and indicators of dampness recorded. The median formaldehyde concentration was 63.6 µg m^{-3} and it was significantly related to the occurrence of SHS symptoms. Dampness and alpha-pinene concentration were also significantly related to such symptoms and the authors recommend that measures should be taken to reduce levels of chemicals and dampness in dwellings.

Sawachi and Tajima (2008) noted that the Building Standard Law was amended in 2002 to specifically focus on formaldehyde and chloropyriphos. The Law sets a performance objective for formaldehyde and requires it to be controlled through material selection and ventilation design. Sawachi reports on a 6 year study to look at changes in formaldehyde and toluene concentrations in dwellings. The results show very clear falls in concentration and the probability of an excess concentration occurring by 2005 was 1.5% for formaldehyde and 0.3% for toluene.

Korea

Cheong et al. (2006) report on a survey of VOC concentrations in 868 newly built apartments in Korea in response to a growing demand for improved IAQ. Six target VOCs were determined according to a protocol whereby the building is ventilated for 30 minutes and then closed for 5 hours prior to air sampling. Average concentrations of formaldehyde (292 µg m^{-3}) and toluene (1016 µg m^{-3}) exceeded guideline values. Formaldehyde concentrations were higher in summer than in winter.

Son et al. (2008) report a further study of VOC and aldehyde concentrations in 120 newly constructed apartments. Concentrations increased after occupancy due to emissions from furniture in particular.

Australia

Brown (2001) measured VOCs indoors and outside in 27 established homes and six new or renovated buildings in Melbourne. TVOC concentrations in established dwellings were about four times those found outdoors. Much higher concentrations were found in the new and renovated buildings.

Europe-wide

Roulet (2006) discussed the relationship between IAQ and the energy performance of a building. This paper notes that steps to reduce energy use in the 1970s often involved use of measures such as weather-stripping to reduce air leakage and this was associated with increased problems of indoor pollution, humidity and mould growth. However, it is argued that with appropriate building design and use it is possible to achieve better IAQ with lower energy use. The paper also notes that in Europe the Energy Performance of Buildings Directive (EPBD 2002/91/EC) requires that measures to save energy should take account of the indoor climate environment and describes the European technical standards concerning energy performance being prepared in support of the EPBD.

Roulet (2006) refers to studies demonstrating that air handling units in mechanically ventilated buildings can be significant sources of indoor pollution themselves, and therefore it is important that clean materials are used for their construction and that the systems are subsequently maintained. The HOPE study of 64 European office buildings is referred to as showing that fewer SBS symptoms occur in newer offices and in those with more floor space per person, and that busy roads, air traffic and more urban locations are detrimental. Also SBS symptoms were correlated with perceived thermal and acoustical comfort as well as lighting. All the ‘healthy’ buildings had openable windows and 66% had natural or hybrid ventilation and two thirds of the less healthy buildings had MV. Three essential objectives to design healthy, comfortable and energy efficient buildings are recommended:

- Prefer passive methods to active ones wherever possible eg use low-emitting materials and controlled natural ventilation, achieve winter thermal comfort with thermal insulation, passive solar gain, thermal inertia and controlled natural ventilation.
- Take account of the user; provide the occupant with the means for some control of the internal environment.
- Adapt the building to its environment and climate eg appropriate thermal insulation, solar protections and ventilation openings, improved acoustical insulation in noisy areas.

4 Other aspects of health and wellbeing

As well as physical measurements of indoor environment parameters, an important aspect of health and wellbeing is people's perception and satisfaction with their indoor environment. Adan et al. (2007) summarised published data for Europe (Table 2).

TABLE 2

Summary of relationships between housing and health from a pan-European study (Adan et al., 2007)

Physical parameter	**Dissatisfaction**	**Health risk**
Thermal comfort	50% highly dissatisfied	Respiratory diseases, cold and throat illnesses, multiple allergies
Daylight	25% highly dissatisfied	Depression, chronic anxiety, fatigue, accidents
Noise	25% people annoyed	Hypertension, depression, fatigue, accidents
Moisture and mould	25% of dwellings: mould growth in more than room	
8% of dwellings	Respiratory diseases, asthma, allergies: smells, dampness	
IAQ (general)	10% dissatisfied	Fatigue, depression, anxiety, respiratory diseases

Levin (2006) refers to the evidence from studies of schools and offices that demonstrates that improvements to the indoor environmental quality (IEQ) result in improved comfort, satisfaction, health, task performance and productivity of occupants. Each of the four categories of IEQ (thermal conditions, acoustics, illumination, IAQ) has significant implications for energy consumption as well as for other resource use and pollution emission.

Loftness et al. (2007) refer to the factors contributing to achievement of designing a healthy sustainable building. In addition to benefits from appropriate air quality, lighting and thermal comfort, workplace ergonomics and access to the natural environment are also identified as providing health benefits to occupants.

Riberon et al. (2006) report on the exceptional heat wave in France in 2003 that caused the death of about 15 000 people. Thirty five per cent of deaths occurred in the home and an investigation of building characteristics identifies that the risk of death was reduced in homes with high insulation and was increased for those on the top floor of a poorly insulated apartment block.

Girman et al. (2008) refers to a heat wave in California in 2006 that killed approximately 160 people. A study of 140 deaths from classic heat stroke found that the deaths were mostly in elderly people and occurred indoors, and in only one case was air conditioning in use prior to death. A further aspect of climate change is that of more extreme precipitation events and associated flooding. Widespread mould contamination can result from such events and CO poisoning has occurred through use of emergency generators when flooding has caused power failure. Other aspects may concern increased risk of some infections such as malaria, higher pollen levels over a longer season and higher ambient ozone concentrations. Potentially the indoor environment could provide shelter from a number of these threats but it is important that the indoor environment is truly healthy. As part of achieving this, the issue of emissions from materials and products used indoors is an important one to address.

NHS (2008) refers to the occurrence of climate change and the expected consequence of heat waves becoming more common in England. Increasing temperatures above 23˚C are associated with excess summer deaths, with higher temperatures being associated with greater numbers of excess deaths. In summer 2006, there were an estimated 75 extra deaths per week in England for each degree increase in temperature. At 27˚C or over, people with impaired sweating mechanisms find it especially difficult to keep cool. Thermoregulation can be impaired in the elderly, chronically ill and those taking certain medications. Older women appear more vulnerable than older men and young children have less ability to sweat and produce more metabolic heat than adults. However, the main causes of illness and death in heat waves are respiratory and CVDs. Part of the cause may be air pollution as well as strain on the heart when extra blood is circulated to the skin to assist cooling. Other illnesses include heat cramps, rash, oedema, syncope (dizziness and fainting), exhaustion and heat stroke. As part of long-term planning to combat effects, a number of recommended actions relate to the built environment:

- increase green space to provide shade and cooling near buildings as well as to absorb CO_2
- increase use of reflective paint on external walls
- use reflective glass in south facing windows
- use cavity wall and loft insulation to reduce heat ingress
- maximise energy-neutral cooling mechanisms eg maximise night cooling ventilation.

A BRE investigation into reported overheating in several properties in London revealed the extent of this problem, which is currently occurring in some urban dwellings. Table 3 shows the maximum and minimum temperatures in each of the rooms in a one bedroom flat monitored for a 1 week period. The temperatures of most significance are the minimum temperatures occurring in each of the spaces. It is evident that within this dwelling the air temperatures remained at unacceptably high levels throughout the monitoring period.

Ventilation in the flat in question is provided by intermittent fans, and background ventilation by trickle-vents. The key to the problem of overheating was not, however, to do with the background ventilation, but with the ability to provide sufficient purge ventilation in this urban property, where other risks (eg noise, security) minimise the potential for window opening, especially at night.

The Housing, Health and Safety Rating Scheme (HHSRS) places a statutory obligation on landlords to minimise risk of hazards (ODPM, 2006). In 2006, a new hazard of excess heat was included in the HHSRS. A temperature above which overheating is considered to occur is now defined, and the extent and duration of this temperature being exceeded is used to define the risk. If a risk is considered to exist, a local authority has a general duty to require appropriate action to be taken to rectify this. There is, therefore, a current legal process that requires actions to be taken in

TABLE 3

Monitored data in an urban property over seven days during August 2006

Room	Maximum temperature (°C)	Minimum temperature (°C)	Average temperature (°C)
Living room	33.9	25.8	28.2
Hall	29.8	26.5	28.0
Bedroom	31.4	25.8	28.1
External	33.5	14.8	19.1

connection with properties to minimise the occurrence of overheating. Currently there is provision for an enforcement notice to be served on the landlord of the property involved – to take action to improve the property and remove this risk.

Rudge and Gilchrist (2006) describe their investigation into evidence of excess winter morbidity among older people at risk of fuel poverty in the UK. Excess winter deaths are conventionally used to quantify health effects of fuel poverty and on average there are 40 000 such deaths annually in England and Wales, mainly from respiratory and CVDs among the older population. The paper describes a pilot study focussed on one area of London and aims to provide a method for predicting the costs to the health service of inefficient housing and the benefits of investing in affordable warmth.

5 Ventilation performance of dwellings

It is common to classify ventilation systems according to two categories (ECA, 2003):

- Natural ventilation whereby air enters into, and exits from, the building through the building envelope by infiltration processes. Ventilation rates vary with weather conditions mainly depending on the wind. Buildings have openable windows for enhanced and rapid ventilation. This type of ventilation is commonly used in the UK and Central Europe. Passive stack ventilation systems have exhaust openings in rooms and air enters through the building envelope and intended openings. The main driving forces are wind and thermal differences between indoors and outside. This has been used more commonly in Nordic and Eastern European countries.
- MV involves fan power to supply and exhaust air from the rooms. The supply air may be heated but not humidified or cooled. The system may recover heat from the exhaust air and may recirculate return air. Windows may be sealed or openable. The systems are common in countries with moderate or cold climate.

A further type of system can be described as hybrid, whereby features of both natural ventilation and mechanical systems are used at different times of the day or season.

5.1 UK

In the UK the Building Regulations seek to minimise risks to health from the build-up of pollutants. Approved Document Part F (AD F) provides guidance on satisfying the requirements of the Building Regulations by the provision of background, rapid and extract ventilation. A whole house ventilation rate of between 0.5 and 1.0 ach is considered to be normally sufficient to control the build-up of moisture (DETR, 2005). This will normally prevent humidity levels exceeding 70% for prolonged periods and so mitigate the associated consequent risk of condensation on surfaces and mould growth. In most UK homes ventilation has been achieved by a mixture of infiltration of air through the structure and ventilation by window opening. Means of achieving the required air change rates are given in terms of trickle-vent size for natural ventilation and flowrates for intermittent and continuously operating fans. AD F also refers to ‘purge ventilation’ which it suggests “can also be used to improve thermal comfort and/or overheating of buildings in summer”.

AD F recognises the following means of providing ventilation mechanically:

- local extract fans run intermittently
- mechanical extract ventilation, both central and decentralised
- whole house MVHR
- single room heat recovery ventilation.

Building airtightness and testing for it is specifically referred to in AD F. AD F refers to a reasonably high level of airtightness, and suggests that a value of 3 to 4 m^3/h per m^2 of envelope area at 50 Pa pressure difference would be the air permeability of the most airtight buildings using normal methods of construction. The minimum allowable standard to achieve is 10 $m^3/(h/m^2)$ at 50 Pa.

Technological developments in the efficiency of both fans and heat exchangers prompted the manufacturers of these systems to request that innovations were recognised for saving energy when compared with more traditional systems. The move to direct current (DC) and electronically commutated (EC) fans has meant that fan power consumption is now a fraction of that of old alternating current (AC) fans. This raises the potential to achieve very closely controlled ventilation at a relatively small running cost. From an energy saving perspective, this provides a level of certainty about ventilation rates and thus ventilation heat loads. To satisfy the industry request, an Appendix (Appendix Q) to the Standard Assessment Procedure – for energy rating of dwellings was developed. This allowed the energy savings resulting from installation of these tested products to be calculated and thereby accounted for in calculation of the SAP value for a dwelling.

Due to the ‘leaky’ nature of UK dwellings, the ventilation rate assumed for MVHR system testing was reduced from the whole house ventilation rates set out in AD F 2006. This correction was undertaken to take account of the fact that in a balanced ventilation system, infiltration will still occur and this would add to the overall building ventilation rate. The assumption is that the combined air change rate is 0.5 ach.

The appendix Q listing has now become a near default requirement for selling continuously operating MV systems in the UK, with competition between manufacturers to produce ever more energy efficient products.

However, one issue, noted by many continental manufacturers of MV products, is that the UK is now only considering energy use at the background ventilation rate in the choice of system. All other aspects, eg ease of cleaning, ability to achieve boost and purge ventilation rates, noise (both air and structure borne), are largely ignored and left to the market to place an economic value.

Following development of the Appendix Q test method, a BRE review of actual achieved ventilation rates and fan energy use in practice was undertaken to assess if the initial assumptions regarding the difference between laboratory test results and actual installed performance had been correct. This investigation revealed that installation practice ranged from very good to appalling. Several properties were found with ducts not connected to room grilles or ventilation rates significantly below that required by the Building Regulations. The results of this investigation were taken on board by the manufacturers’ trade associations and led to the start of development of training schemes for installers.

Projects to assess the energy efficiency of MV systems have found that greater performance could have been achieved if tradesmen undertaking the installation had a better understanding of the systems (DETR, 2005). Advantages and disadvantages of the systems are outlined, eg mechanical supply ventilation is relatively simple to apply and operate and air can be filtered, but the system can be perceived by occupants to have high running costs and be noisy. Also the system requires maintenance, its effectiveness depends upon the building layout, it is prone to occupant tampering and research into its use is limited.

Guidance on design and performance of systems to achieve Code Levels 5 and 6 is provided by the Energy Saving Trust (EST, 2008). MVHR is described as a low maintenance technology that requires little user intervention. However, it is considered important that householders are provided with a sheet detailing maintenance regimes and other checks, and that manual switches and automatic humidity or other sensors are clearly marked. The guidance also states that studies have shown that MVHR systems can provide health benefits through the reduction of dust mites.

Studies in many European countries have shown that MV systems may cause adverse health effects although the causal factors are not well understood (ECA, 2003). Risks in the performance of MV include:

- HVAC components may be dirty when installed or become dirty and release pollutants with odours.
- poor control of indoor temperature due to absence of cooling
- low humidity in winter
- noise generated by forced airflow and fans
- draught caused by forced airflows.

Recent BRE discussions with UK manufacturers of MVHR systems suggest that there is no market for replacement filters with several reporting no filter sales at all. This suggests that maintenance is not being undertaken – even at the most basic level.

Systems with mechanical cooling can have additional risks relating to cooling coils because of the potential for microbial growth and presence of biocides. Air recirculation can result in dispersion of indoor generated pollutants within the house and involve higher air velocities and associated noise and draughts, and supply ducts may become contaminated with indoor-generated pollutants. All-air heating and/or cooling systems are however, not common in the UK.

AD F is currently being reviewed and it is very likely that part of the proposed changes will include reducing the allowance for infiltration currently available for MVHR installations. The reasoning behind this possible amendment is the very fast change in airtightness that has been achieved since the last review of AD F in 2005/06.

In addition to this potential change, and following the investigation undertaken by BRE into installation practices, a requirement to commission systems and sign off the achieved airflow rates in each room served by a MV system is proposed. To assist installers to achieve good installation practice, an installation and commissioning guide is currently being developed as a supporting document to AD F. A further proposal for MV systems is to require the sound tests, set out in the EN13141 series of standards, to be undertaken and the results published. It is noted that while this will provide information on the performance of the fan; there are no proposals to require installed noise levels to be measured to ensure that acoustic/anti-vibration isolation is appropriate and noise nuisance is minimised, particularly in bedrooms.

Other issues of note which it is understood are currently not being considered in the AD F review are: the appropriateness of demand controlled ventilation, minimum ventilation rates for unoccupied dwellings and spaces which have not been defined and an absence of any real guidance on cleaning ventilation systems.

As part of the background to the changes to AD F, CLG (2009) has published a report on an investigation into the effectiveness of a range of ventilation strategies. Two buildings were modelled – a flat and a detached house, with a range of ventilation strategies including: passive stack, intermittent extract and continuous ventilation strategies, including supply, extract and balanced. The envelope leakage rate of both buildings was set at 3 $m^3/h/m^2$ at 50 Pa. The aim of the investigation was (for a given occupancy pattern and defined set of pollutant emissions) to determine how effective each ventilation strategy was at preventing each room exceeding a defined upper limit. The simulations considered two extremes: windows and internal doors remaining closed and windows opened for purge ventilation twice a day and all internal doors left open.

The first set of results indicated that all ventilation strategies failed when the ventilation rates were set to those defined in AD F 2006. The simulations were therefore re-run with increased ventilation rates. This proved more successful, but the study concluded that:

- not all ventilation strategies achieved the same IAQ levels at a given ventilation rate
- internal transfer of air was critical and if doors remained shut, transfer grilles were required

- the RH exceeded the recommended levels set out in AD F 2006 in all ventilation strategies. The validity of these recommended maximum levels is currently being investigated as part of a CLG project.

Based on the findings of the project and discussions with industry, CLG recommended:

- the prescriptive approach to defining ventilation rates should be continued, as it is preferred by industry
- emission characteristics of materials should be investigated leading to materials labelling
- performance standard modelling is considered as appropriate for future assessment of ventilation strategies, but it is acknowledged that it is currently not possible for the current review of AD F, as the development and agreement by industry of the validity of the model would require significant time.

5.2 Other countries

Canada

Prowskiw G (1992a) describes tracer gas tests and air distribution measurements undertaken in three new energy efficient houses to evaluate the performance of the MV systems and determine compliance with requirements of CSA F326 (residential MV systems). The study included testing of five types of MV design. All met requirements for minimum ventilation capacity for dwelling units (lower default value of 0.3 ach) but three did not meet the room airflow rate requirement. Only one of four systems tested met the requirements for exhausts from kitchens and bathrooms (kitchen exhaust 50 ls^{-1} intermittent and 30 ls^{-1} continuous; bathrooms 25 ls^{-1} intermittent and 10 ls^{-1} continuous). Failings were due to a combination of duct leakage and incorrect flow distribution.

The National Building Code of Canada (1985) requires all dwelling units to have an MV system capable of providing 0.5 ach and this was modified in 1990 to 0.3 ach. CSA standard F326 was adopted as the ventilation standard for R-2000TM in 1991.

Rousseau (2003) summarises information on heating, cooling and ventilation systems and equipment for low-rise residential buildings with regard to their effect on IAQ. The review includes consideration of the needs of environmentally hypersensitive occupants.

Finland

Kurnitski and Seppanen (2008) note that Finland is the country with the highest market penetration of mechanical supply and exhaust ventilation in the EU. Almost all new dwellings are fitted with MVHR systems. This move has come about due to changes in regulation in 2003, which increased guideline ventilation rates from 4 to 6 l/s per person and required a minimum of 30% heat recovery from exhaust air. This changed the ventilation practice in Finland from primarily mechanical exhaust, to balanced supply and exhaust with heat recovery.

The Finnish Indoor Climate and Ventilation of Buildings Regulations and Guidelines, D2, 2003, also recommend that supply air should normally be filtered and recommends a filter class of F7. In rural locations this may be lowered to F4. However, Railio (2005) notes that in urban locations filters of F8 or F9 are recommended for the supply air.

D2 provides significant detail on how the cleanliness of the ventilation system is to be ensured during construction, and what access is required to maintain cleanliness during its operational life. This extends to the requirement that components ‘should have such inner surfaces that it is easy to maintain system cleanliness’. Discussions with Finnish manufacturers have revealed that this has resulted in most fan units having painted metal internal surfaces, which are easy to regularly wipe clean. It was noted during these conversations that this is not the case with many of the products currently on the UK market, which would be difficult to clean due to the exposed materials and the limited access to all areas of the products.

In addition to the requirements for system cleanliness, Kurnitski and Seppanen noted that the creation of emissions tests for building materials has led to a remarkable reduction in material emissions. It is suggested that this may have consequences for airflow rates; however, to date this has not been fully addressed. It was reported that in 2007, more than 1100 building material products and 100 clean ventilation products achieved the emissions criteria. It is claimed that this suggests that the great majority of building materials now on the Finish market are labelled for emissions.

Kurnitski et al. (2007) report on a study of 102 newly built detached houses in Finland. The study found that the fan speed was very rarely changed and that the average measured air change rate was approximately 0.4 ach. Measurement of the airflow rate revealed that only 57% of the houses complied with the regulations and that in most cases this was a result of occupants reducing fan speeds to reduce noise. Complaints of noisy systems correlated closely with noise levels in bedrooms. Evaluation of MVHR products from Finland by BRE suggests that fan installation location is different to most other countries and Finnish manufacturers confirmed that this was aimed at minimising noise transmission in the supply air distribution system.

France

Durier (2008) noted that the design and installation requirements for MV systems are used by insurance companies to cover the risk of damage linked to the malfunctioning of the ventilation systems. The market in France is dominated by exhaust air systems, with and without demand control. The control of the ventilation is usually achieved on humidity only. The market share for balanced systems is suggested to be less than 2%.

A study reported by Durier found that 40 to 50% of dwellings checked did not reach the minimum exhaust airflow rate required by the regulations. It was noted that this highlights the need for improved installer training, increased quality of construction process and requirements for commissioning after installation.

USA

In America, Sherman (2008) noted that ventilation systems have only a very little penetration into the market, and that the very common forced air heating systems installed in US dwellings make the products appropriate to most of the USA very different to those being installed in Europe. However, Sherman does note that as airtightness increases, along with concern for comfort, IAQ and most importantly energy sales are expected to increase. The standard used in USA for ventilation and IAQ is the ASHRAE Standard 62.2-2007 for dwellings, which sets out the required ventilation rates as the sum of fresh air required to dilute background sources plus sources attributable to occupancy. The air change rate is therefore a function of both floor area and occupancy, ranging from less than 0.3 ach for a two bedroom house with a floor area of 5000 ft^2 to 0.55 ach for a two bedroom house with a floor area of 500 ft^2. It is, however, noted that the air change rates are significantly below national standards in other countries and that this rate is under continuous review.

Sherman also reported on a study into window opening that indicated that only about 20% of occupiers in recently constructed dwellings actually opened windows to achieve adequate ventilation. Reasons for this were sited as noise, dirt, security, draughts and privacy.

In both the USA and Canada the issue of duct cleaning has been investigated and the EPA (1997) in the USA concluded that duct cleaning has never been shown to prevent health problems. Additionally, studies do not conclusively demonstrate that the dust levels in homes increase because of dirty air ducts. Since the publication of this review however, levels of airtightness in the US have increased significantly. In Canada the Canadian Mortgage and Housing Corporation (CMHC, 2007) noted that duct cleaning is claimed to provide better IAQ, reduce presence of mould and allergens, and remove dust from houses. The report comments that “if you expect duct cleaning to make these improvements, you may be disappointed. It is difficult to find objective and independent research which substantiates these claims”.

6 Construction and ventilation provision in highly energy efficient homes

6.1 UK

In 2006 there were 16 000 builders registered with the NHBC. A large majority of homes are built by a relatively small number of building companies, eg in 2006 51% of new home registrations were made by 24 builders. About 160 000 new units per annum were built in total.

Davis and Harvey (2008) undertook a survey of views of homeowners and housebuilders on zero carbon homes. When asked about airtightness, the general perception of homeowners was that fresh air is required to maintain the health of a home and its occupants. Airtightness was a source of great concern for homeowners because of fears that increased airtightness may restrict access to fresh air and ventilation. Housebuilders were relatively optimistic about their ability to build to the required standards of airtightness, but expressed concern about air quality and the welfare of homeowners. Mechanical whole-house ventilation systems were thought likely to be required to ensure the air remains safe for habitation and there were concerns about the service and maintenance required by such systems. It was suggested that homeowners may turn off the system thinking it would save energy and also open windows and doors to gain fresh air thereby reducing energy efficiency. Also there was concern that use of highly insulated lightweight structures could result in an uncomfortably warm environment in summer and thereby lead to a need for air conditioning.

For high level CSH homes, builders considered that they were most likely to use timber frame or conventional brick and block technologies. Housebuilders were concerned about the practicality of the various microgeneration technologies available. Microgeneration is the small-scale, off-grid production of energy, including heat, using renewable sources. Options include systems specific to an individual property, specific community, development or offsite scheme. Builders considered the most likely systems to be deployed as solar thermal (to heat water), photovoltaic (PV) (to generate electricity), ground source and air source heat pumps (for space and possibly water heating).

On the BRE Innovation Park at Watford there are a number of demonstration homes incorporating construction practices and new technologies that are being developed to meet the requirements of zero carbon homes. These include the first two UK homes built to attain Code Level 6 of the CSH (www.building.co.uk/sustain_story.asp?storycode=3111357): the Kingspan Lighthouse and the Barratt Green House.

6.1.1 The Kingspan Lighthouse

The high thermal efficiency and airtightness of the building envelope of the three storey house is achieved by use of prefabricated panels consisting of oriented strand board (OSB) facing containing rigid polyurethane foam. Other features include timber cladding, monopitch roof, a wood-pellet fired biomass boiler, PV panels, solar thermal panels and external shutters to block direct sunlight. Passive cooling and ventilation is provided by a 'wind catcher' located on the roof. When open, cool outside air enters and descends through the house encouraging air movement by the stack effect. An electrically driven whole-house MVHR system provides background ventilation.

6.1.2 The Barratt Green House

This is a three storey, three bedroom home constructed of H+H Celcon aircrete planks glued together, insulated and rendered externally and conventionally dry lined. Air and water is heated by an external air source heat pump (powered by PV panels) with hot water pipes running into the house as would be the case for a district heating scheme. The MVHR system provides fresh air to all liveable rooms and extracts stale air from all wet rooms and the kitchen. An array of PV panels mounted on the roof of the home powers appliances.

Construction details and lessons learnt about achieving an airtight building fabric are described by Gaze (2008) for the 'Lighthouse' as well as three other energy efficient homes constructed on the BRE Innovation Park prior to June 2007. The 'Green House' was constructed at a later date. Findings include the need for joints to be gasketed or taped, rather than relying on mastic and foam sealants, that simple designs are easier to make airtight as well as panel systems, as these have fewer joints, and that post-construction work to improve airtightness is problematic. It is commented that gaskets, and to a lesser extent tapes, appear to be preferable for sealing since they give off fewer VOCs, which in turn require good ventilation to remove them to improve indoor air. Gaze et al. (2008) summarise lessons learnt with respect to energy sources, overheating and ventilation. These include placing bedrooms downstairs to keep them cooler, increasing thermal mass by use of additional heavy panels, tiles and plaster skim, and consideration of prefabricating MVHR systems and their ductwork offsite to make conformance to specification more likely.

Other case studies of homes built according to the CSH are described by CLG, 2009a and as part of the Creative Energy Homes Project at the University of Nottingham (Appendix C). Pitts and Chan (2005) describe the Beddington Zero Energy Development (BedZED) which is a housing scheme in London that incorporates some mixed use commercial units and community facilities. Some features include airtight construction, high fabric insulation, high thermal mass, heat recovery ventilation and a combined heat and power plant using waste timber carbon neutral fuel source.

6.2 Other countries

Europe – PassivHaus

Henderson and Matlock (2007) summarise the PassivHaus standard, which is a performance-based approach developed for cold-climate housing. This standard is being used in Germany, Austria and Ireland.

The PassivHaus standard was developed in Germany in 1996 by an independent private research institution with a focus on research and development of highly energy efficient buildings and systems. From 1997 to 2002, the European Commission funded the development of the PassivHaus standard as a leading standard for energy efficient design and construction. The PassivHaus Programme, with over 5000 houses built prior to 2005, has promoted development and production of components such as low capacity compact HVAC units, windows and doors and innovative building systems. Key PassivHaus standards for new construction are as follows:

- no more than 10 Watts of heating capacity per m^2 of conditioned space
- no more than 15 kWh of heating energy used per m^2 annually
- a total onsite consumption of less than 120 kWh per m^2 annually.

The PassivHaus Planning Package 2007 states that average air change rates should not fall below 0.3 ach, and typically be at 0.4 ach (Feist et al., 2007). Air leakage rates are very low with default values assumed to be 0.042 ach. Feist (2000) recommended that in winter the ventilation rates should be lowered to maintain internal humidity values at acceptable levels. Matlock and Henderson comment that there is a need to demonstrate whether these buildings actually perform as well as indicated by the modelled data. Some further information about the standard is provided in Appendix D.

As the PassivHaus standard is measured in terms of absolute energy use for space heating, it is not possible to compare it directly with the CSH and Building Regulations in the UK as these set standards according to reductions in CO_2 emissions for space heating, water heating and lighting (BRE, 2008). Typically a new build PassivHaus can be expected to achieve the energy requirements of Code Level 4 without renewable technologies being specified. The fabric requirements for Code Level 6 are based on the PassivHaus standard. BRE (2008) provides guidance on PassivHaus requirements and examples of construction features appropriate to meet the standard. The MVHR heat recovery efficiency should be greater than 75% and the system should use a low specific fan power. While occupants are able to open windows the MVHR provides the fresh air. It is estimated that because of the highly airtight structure (1 $m^3/(h/m^2)$ at 50 Pa or less) it would be necessary to open all windows for 5 to 10 minutes every three hours to provide adequate ventilation and therefore MVHR is the practical solution.

Feist et al. (2001) describe the CEPHEUS project (Cost efficient passive houses as European standards) that involved the construction and evaluation of 221 housing units built to PassivHaus standards in five European countries (Germany, Austria, Sweden, France, Switzerland). It involved a range of different buildings designed to meet the standards and considered energy performance and investor and purchaser acceptance and user behaviour. The key features of the PassivHaus homes were:

- a highly insulated thermal envelope
- MV for continuous supply of fresh air and a heat exchanger to recover heat from outgoing air to warm incoming air. Also sub-soil preheating of fresh air may be applied
- passive solar gain optimising use of south-facing glazing, often with use of triple low emissivity glass
- energy efficient appliances
- use of renewables to meet the remaining energy requirements.

A diverse range of construction types was used, ranging from reinforced concrete roofs, to rafter roofs or lightweight construction. Walls included sand-lime block or concrete, timber post and beam and prefabricated elements. Floors were often a reinforced concrete slab with insulation, but in other cases lightweight timber construction was used. An important requirement was an airtight envelope and the project aimed for post-construction pressurisation tests to achieve a value of 0.6 ach. The airtightness requirement was achieved in 8 of 14 separate development sites. Also, adjusting the balance of the ventilation system was an important aspect of the pre-occupancy work.

There was no evaluation of air pollutants, but some projects included measurements of temperature and sought information on occupant satisfaction with the buildings. Mean winter temperatures were above 20°C in all buildings (range 17 to 25°C). There was data for summer in only two projects; mean temperatures ranged from 21.9 to 23.6°C and there were only exceptional instances of temperatures above 27°C in some houses. A substantial majority of occupants considered the indoor climate to be good or very good in winter and 88% were satisfied or very satisfied in summer. Air quality was rated as good or very good by 95% of occupants. The energy performance targets were met in the 11 sites successfully monitored during the first heating season after construction.

The results of the CEPHEUS project were further discussed and summarised by Feist et al. (2005). They refer to the essential need for good solar protection to avoid overheating both in winter and summer. Passive cooling by night time natural ventilation can be used in summer and while the ventilation system can be used the ventilation rates are too low for most effective cooling. They refer to the importance of considering the layout of the ventilation system at an early stage of the design process in order to take account of space for ventilation equipment and ducts and the possibilities for cascade-flow ventilation (where air is supplied to some living areas and removed in others to create a flow through the building). The duct system should be easily accessible for cleaning, but filters should be used to avoid deposition of dust. Filters must be changed regularly to avoid high pressure drops and maintain hygiene. Kitchen hoods should preferably be operated in recirculation mode with a high quality filter in the hood. Ventilation is set to supply outdoor flow of 5 to 10 l/s corresponding to air change rates of 0.3 to 0.6 h^{-1}. Relative humidity depends upon the absolute humidity of the outdoor air, the air change rate and amount of internal humidity production. They refer to the likelihood of RH being below 30% if air change rates exceed 0.4 h^{-1}. The system should allow a minimum supply setting for times of zero occupancy of 0.2 h^{-1}.

Feist et al. (2005) refer to interior finishes and furniture as important sources of air pollutants. They comment that airflows can be kept low if these sources are reduced as far as possible and only non- or low-emitting materials are used, but offer no further guidance about how such materials may be identified and sourced. The maximum temperature of the supply air in the heater is restricted to 55°C and this is to avoid odour emission from dust carbonisation on heated surfaces. Air recirculation is not recommended because odours and pollutants could be redistributed within the dwelling. The paper refers to chamber studies of airflow to investigate thermal comfort and draughts and to demonstrate effectiveness of different designs. It reports measurements in one case study dwelling concerning the performance of a wood stove for additional heating provision.

Balvers et al. (2008) investigated air quality and ventilation performance in four houses built to the PassivHaus standard in the Netherlands. A questionnaire was used to record information about characteristics of the house and the occupants and their use of facilities, including use and maintenance of the ventilation unit. Also measurements of airflow, temperature, RH, CO_2, CO and formaldehyde were undertaken over a 3 week period, but the paper does not describe the time of year or the external conditions when the monitoring took place. The authors consider the most important finding concerns the manner in which the occupants used the ventilation systems. The system was set at default position one, that for lowest flow, for almost all of the time in all properties. This is the lowest of three default settings intended for when residents are away from the home. Residents of one property reduced the flow setting further to minimise energy consumption.

One household complained of low humidity and decided not to use the cooker hood (over a gas cooker) and allow the dishwasher to dry with the door open to try and increase the humidity. Indoor air temperatures were around 22°C in the living room and the highest humidity was 55 to 60% in one house but quite low in two other houses: 35±5% and 40±10%. One house used gas rather than electric cooking and CO concentration peaks were observed in this property. Concentration peaks in another of the properties occurred when guests smoked in the home. Daily peaks in formaldehyde concentration were reported in two houses; one of the graphs shows a concentration of 1.6 ppm in one case which, if accurate, considerably exceeds the WHO guideline value for formaldehyde (WHO, 2000). CO_2 concentrations are described as not exceeding 1000 ppm very often except in a bedroom of one property where increasing the ventilation was still insufficient, and in a bedroom of another property where the air inlet was blocked by a closet. The authors conclude that the houses are potentially healthy and comfortable, but that extra care is required when installing the ventilation equipment to avoid a reduction in airflow and that residents must be educated in the proper use of the system.

In Switzerland a low energy label for buildings called MINERGIE-P was launched in 2002 that is strongly based on the PassivHaus standard (Mennel et al., 2007). There are some differences due to application of Swiss rather than German product standards, but the essential characteristics are the same.

Hungary

Hermelink (2006) describes the decision process for selecting an appropriate ventilation system to be used for upgrading a panel system property in Hungary. The aim is to transfer knowledge gained from ultra-low energy and passive houses to a sustainable retrofit of property, there being a large stock of panel system buildings in Eastern Europe. Criteria for evaluating different ventilation systems were identified as follows:

- efficiency of heat recovery
- cost – investment, operation and maintenance
- disturbance of installation
- noise when operating
- space requirement
- risk of abuse by occupants and strangers
- requirements for fire protection and other legal requirements
- comfort (thermal and odours)
- complexity for fitter
- ease of handling for occupants
- market availability of system and parts.

The chosen system involved one small ventilation system, comprising two high-efficiency DC fans for fresh and exhaust air and super-efficient air-to-air heat exchangers in each flat, and radiators in each living room. Concerns raised about kitchen smells and elevated CO_2 from gas cooking were addressed by use of an additional recirculation cooker hood and provision of an over-sized MV system to provide sufficient ventilation during cooking.

The Netherlands

Beerepot (2006) reports on the changing ventilation strategies applied in homes in the Netherlands in response to changing demands for energy efficiency in building regulations. There has been an increasing use of systems using mechanical inlets and outlets (40% of new build in 2001). Research into occupants' self-reported health has not revealed increased problems in homes with tight energy standards, but the population in such homes is biased towards young persons with high education who spend much of their time outside their homes. Discussions between Dutch MV systems' manufacturers and BRE have revealed that this move to decentralised systems was the result of the frequent bad system installation practice, which resulted in poor performance of centralised systems.

Hasselaar (2008) refers to studies and discussions that have considered the indoor environment in passive houses and other low energy houses with similar characteristics. Inspections were made of two passive houses in the Netherlands where residents were generally positive about the properties noting small temperature fluctuations and good acoustic shielding from the outside. Negative comments were that too much heat was supplied to the bedrooms and not enough to the living room, that the low external noise makes internal noise more noticeable (fans and airflow in dampers), occurrence of low ventilation volumes in bedrooms, and unfamiliarity with the complex system – with concern about potential maintenance costs.

The paper refers to other work in the Netherlands where residents of newly constructed properties reported health complaints which they associated with the heat recovery ventilation system. Ventilation capacity was generally below requirements and the quality of the indoor environment was inadequate in respect to noise, draughts, CO_2, formaldehyde and high indoor temperatures in summer. Complaints included: that the fresh air is not fresh, that the system generates noise at standard speed and that ceilings or walls become dirty from deposition of particles. The percentage of dwellings where occupants complained of perceived health problems was highest (~40%) for symptoms associated with the nose, eye irritation, headache, tiredness and insomnia.

A further Dutch report is referred to, that describes a reduction in air volume of 15 to 25% caused by dirty filters. Filters and units tend to be cleaned at intervals of 6 months to one year, the MVHR unit once in 8 years and ducts after 15 years or longer. It is suggested that cleaning at shorter intervals is required. Test houses are referred to as part of an Ecobuild-research project where complaints of high radiant temperature of sunlit double glazing (33 to 40°C) were reported.

The author proposes a number of improved design and performance criteria for energy efficient homes including: a closed kitchen to contain pollutants, a covered outdoor area for drying washing, filter cleaning every 2 weeks, an indoor maximum acoustic level (28 to 30 dB(A)), HRV used only when heating required and permanent basic natural ventilation allowing safe summer and night use.

Europe: Smart Energy Home

The Smart Energy Home initiative has been established by key industry players in Europe to lead and influence the way we build and live in homes. It aims to promote research and the uptake of technology for less energy consuming, smarter and healthier homes. Part of the initiative is DEMOHOME whereby at least four demonstration projects are to be built integrating zero energy consumption, comfort, safety, health and sustainability into well designed and planned homes (Klotz 2008, BASF 2008,).

Canada

The R-2000TM Program sets performance standards for the design and construction of energy-efficient new homes. It is based on targets for the maximum amount of energy that is required for space and water heating. The target varies according to geographical location, size and fuel type. Standard operating conditions are used in the calculations for other variables, such as lighting, appliance and interior loads. It includes measures to achieve good IAQ including requirements for ventilation and selection of low-emitting products. Further details are provided in Appendix E.

Henderson and Matlock (2007) review options for approaching net zero energy housing in Canada. The term Net Zero Energy Housing (NZEH) rose out of the US Department of Energy's Zero Energy Homes research initiative that started in 2000. In 2006, Canada Housing and Mortgage Corporation's (CMHC) EQuilibrium Housing Pilot Demonstration Initiative provided targets for Canadian homebuilders and developers (CMHC-EQ, 2007). 'Net zero energy housing', as defined by CMHC, describes a home that produces as much energy as it consumes annually. This is done through a variety of means, including:

- reducing energy loads through a climate-responsive, high-performance building envelope and use of energy efficient appliances and lights throughout the house
- increased use of passive solar cooling and heating techniques
- high-efficiency mechanical systems that match the lower energy requirements of the home
- space and water heating assisted by commercially available solar thermal systems and heat pumps
- electrical use offset by grid-connected commercially available PV systems.

Determining cost-effective ways to retrofit houses to meet net zero energy targets is regarded by CMHC as a key element to both energy security and climate change mitigation (CMHC, 2008). To date, most NZEH initiatives have been focussed on new construction. Its study looked at ways to approach net zero energy in the more than 12 million existing houses in Canada. The age and style of a house, as well as variations in regional and historical construction practices and materials choices, all require consideration.

NZEH considers that the technology and materials are available to reduce energy loads significantly in existing houses, by a factor of 7 to 9. However, getting to net zero energy in existing houses is completely dependent on the cost of the add-on renewable systems that take the house to net zero energy. Solar thermal systems are market-ready with a reasonable payback period, and are a more readily accepted option by homeowners. If there were financial incentives and mechanisms in place, roof-mounted solar thermal systems would become a much more commonplace sight in Canada. PV systems are currently very expensive, with long payback periods for small systems. Until there are reasonable incentives to purchase and operate these systems (tax rebates, purchase incentives, 'green power' premiums for grid-connected systems), it will be nearly impossible for homeowners to operate their houses as a net zero energy home.

USA

Price et al. (2006) describe the development of the US EPA labelling program to recognise new homes that are built with a comprehensive set of features designed to enhance IAQ. The program is voluntary and coupled with the EPA Energy Star Program for new homes. The specifications are designed to be implemented by homebuilders and trade professionals within normal construction processes. The EPA targeted IAQ because of the relationship of human health to IAQ and the fact that IAQ is closely associated with the energy improvements builders are including in homes. The label requires all the defined requirements to be met.

In the past IAQ was not widely recognised by builders but issues such as radon in the 1980s, and mould in the 1990s, and associated legal cases raised the profile. More recently suppliers of HVAC products have promoted benefits for IAQ. In recent years, improvements in energy efficiency have evolved in a large part through use of materials and designs providing a more airtight structure. With tighter homes, concerns were raised about reduced air exchange resulting in increased pollutant levels. The label specifies requirements for management of moisture, ingress of radon, for heating, ventilating and air conditioning, including use of mechanical whole-house ventilation, use of low formaldehyde emitting materials and carpeting and measures for pest control. Further information on these requirements is given in Appendix F.

China

Pitts and Chen (2005) undertook a review of the awareness and potential for development of zero carbon housing in China. Energy use in buildings accounted for about 23% of the national total and was increasing due to changes in lifestyles and people's expectations. Pressures to build have meant that regulations supporting low energy design and sustainability had not been strictly enforced. A process of education is required concerning costs and benefits to exploit the considerable potential for zero emission development.

7 Research needs concerning the indoor environment in energy efficient homes

7.1 Possible consequences of characteristics of highly energy efficient homes

A number of characteristics of highly energy efficient homes can be identified as having a particular impact on IAQ and other aspects of the internal environment that could impact on the health and wellbeing of building occupants. These impacts could be either beneficial or disadvantageous. It is also possible that some characteristics result in no net change to health and wellbeing relative to that experienced in less energy efficient homes. In that case consideration should be given as to whether the current state of the art is acceptable for the future, or whether some form of intervention is required to achieve improvement.

There is no published study of highly energy efficient homes in the UK that monitors the range of air quality and other factors that can affect occupant health and wellbeing. Of course, only a limited number of homes currently exist at Code Level 4 and above, and the definition of zero carbon (Code Level 6) is currently the subject of government consultation. However, it is notable that comprehensive studies of the indoor environment of UK homes are few. The BRE study of 37 homes built following introduction of the 1995 Building Regulations measured airtightness, ventilation rates and several pollutants (NO_2, VOCs, formaldehyde, CO) over two sampling periods during one winter and one summer (Dimitroulopoulou et al, 2005). These homes, all in southern England, were found to be no more airtight than the general building stock, and none of the homes were mechanically ventilated. The Indoor Environment Survey of England addressed several pollutants (NO_2, VOCs, formaldehyde, CO) but it was carried out over 10 years ago. The ALSPAC study also covered mites, bacteria and fungi, but this was limited to a particular population group in 174 dwellings in one city and was carried out over 15 years ago (Berry et al., 1996, Humfrey et al., 1996).

Possibly more informative to our understanding of highly energy efficient homes are studies in other countries with experience of building airtight homes, particularly for very cold climates, such as in Canada, central Europe, parts of the USA and Scandinavia. Certainly these provide experience of mechanically ventilated buildings, often with heat recovery, which is likely to be necessary to meet targets for Code Level 5 and 6 homes. However, there are differences to the UK with regard to climate, local building practices, sourcing of materials, and the economic, cultural and social characteristics of the occupants. It is notable that even for PassivHaus the published studies relating to occupant health and wellbeing have only addressed thermal comfort and occupant satisfaction, and none has been undertaken in the UK.

Because of its central role in determining the exposure of the population to air pollution, a case could be presented for more research into IAQ in homes. For the purposes of this review, however, the main features of highly energy efficient homes are considered and their possible impact on air quality parameters relative to current Building Regulation requirements.

7.2 Increased airtightness

Taken alone, with the assumption that sufficient air for ventilation is provided by alternative means, increased airtightness means that provision of background ventilation is through identifiable and controllable locations. As pollutants can interact with surfaces (eg reaction of ozone, deposition of particles) this could influence the composition of incoming air to some extent. Also some materials in the structure can release chemicals that are transported to the occupied space (eg formaldehyde from urea formaldehyde cavity wall insulation) and depending upon the nature of the façade, this could offer some protection to such ingress. Appropriate designs preventing cold bridges and dampness could reduce the likelihood of fungal and bacterial proliferation in the structure. The relative merits would depend on the quality of supply air achieved in the airtight structure; this could involve interaction with possible additional sources such as oil and deposited dust in ductwork.

The ability to be selective about points of ingress of background ventilation provides some opportunity to consider sources of outdoor pollution in siting ventilation provision. This may offer advantages for housing located for example on a busy road, particularly where a canyon effect may trap pollutants. A possible disadvantage of such controlled ingress is that occupants may be empowered to close/turn off the air supply and reduce the background supply to a level below that appropriate for maintenance of a healthy indoor environment. Also it is necessary for the ventilation provision to ensure adequate mixing in the room to avoid short circuiting by air moving directly from inlet to outlet.

7.3 Increased winter internal temperature

Warm conditions should be more readily maintained in winter and this has direct benefits for the health of the section of the population unable to maintain temperatures in current homes to avoid increased risks of respiratory and CVD. A warmer home should reduce condensation problems for equivalent moisture in air loadings and thereby reduce the risk of microbial growth on surfaces. The warm conditions could favour proliferation of dust mites, although reduced humidity should have an opposing effect. The warmth could increase off-gassing from materials to some extent. The ability to maintain higher temperatures may result in less use of unflued combustion devices to provide additional heat, and thereby reduce the associated risks of exposure to the indoor pollutants generated. A further benefit for health and wellbeing could result from lower costs for heating of homes, thereby making available income that could be used to improve other quality of life aspects such as diet.

7.4 Summer internal temperatures

Appropriately designed homes with solar shading, high insulation and adequate and controlled ventilation could offer better protection of occupants against elevated temperatures during heat waves. This potentially has a significant beneficial effect for health and wellbeing and can help counteract consequences of the expected increase in incidence of heat waves in the future due to climate change.

7.5 Mechanical ventilation

The effectiveness of MV strongly depends upon the design of the system, its installation and the level of in-service maintenance undertaken. Provided that the required rates of air supply are achieved and there is effective mixing, then pollutants should be diluted and removed at the intended rate. Possible advantages are the potential to remove particulates from the incoming air (such as pollen) by filtration, and potential for the air to be drawn from a location where outdoor pollutants are considered to be least, eg away from roadside and combustion appliance exhausts. Particular concerns are that while performance of a system may be demonstrated at commissioning, building occupants may interfere with its operation, and maintenance may be inadequate because of poor awareness of the need for, and reluctance or inability to pay for, routine servicing. Difficulties of access to ducting and filters can further discourage appropriate maintenance operations. The chief concern therefore is of reduced air supply performance over time and a build-up of dust that can be a source for microbes, chemicals and allergens in the indoor air.

7.6 Heat recovery aspect

The PassivHaus standard recommends use of recirculating cooker hoods to prevent loss of energy in outlet air. This potentially could result in higher levels of gases and particles being released into the living space than if the hood were removing the air to the outdoors. Even if the filtration in the recirculating hood was adequately maintained it would probably be ineffective for removal of some pollutants such as CO, moisture and ultrafine particles.

7.7 Materials for construction

A number of drivers such as regulation, cost, construction methods, material availability, sustainability and consumer preference influence the selection of materials used for construction. Highly energy efficient buildings in particular use materials providing higher levels of insulation. Some of these materials have the potential to release chemicals into the indoor air, particularly those incorporating polymeric materials. Therefore the rate of emission may possibly be higher than in less insulated homes unless products are selected according to criteria limiting the emission.

Currently there are few requirements for emissions within product standards and there is little evidence in the literature for measurement of the air pollutants identified in the performance criteria of Part F of the Building Regulations. The European standards organisation (CEN) is mandated to prepare standards for determining the emissions of dangerous substances to indoor air from construction products and this should lead to product standards that declare performance with respect to emissions. A number of national and industry based schemes exist in some other European countries to identify and encourage the use of low-emitting products. While these remain largely voluntary, some aspects are now mandatory in Germany. There is also an active movement towards harmonisation of these voluntary schemes in Europe (ECA, 2005, Crump, 2009). Some schemes, such as that operating in Finland, consider the air quality in the whole building rather than just on a product-by-product basis. In the USA, the EPA and the LEED schemes for sustainable buildings promote the use of low-emitting products (USGBC, 2008).

7.8 Ground contaminants

The nature of the floor construction and use of protective membranes probably outweighs any effect of the internal conditions in the home. However, any depressurisation resulting from a ventilation system could draw contaminants such as radon into the property and any pressurisation should have some protective effect. Higher temperatures indoors could increase the stack effect whereby air is drawn into the property to replace rising warm air.

7.9 Recommendations for further research

It is recommended that research is required in two broad areas:

- Addressing the performance of products and designs for high energy efficiency homes and provision of guidance for installers and users.

- Post-commissioning and post-occupancy evaluation of performance of buildings meeting Code Level 4 to 6 requirements.

The following topics relating to products and design require further knowledge and provision of guidance:

- Noise is cited as being one of the key drivers to occupants reducing fan speeds. This effect has been directly correlated to noise in bedrooms. It is therefore critical that installed noise, both structural and airborne, is minimised if mechanical systems are to be accepted and kept at the commissioned settings. Minimum standards for installation of acoustic insulation and anti-vibration mounting need to be determined and introduced.
- The requirement for cleaning fan units and ductwork needs to be thoroughly investigated. Evidence from the USA suggests that a market has been created which is based on fear, with cleaning costs being high. The rate of build-up of dust and dirt within fan units and ducts in UK dwellings needs evaluating and guidance produced on good practice maintenance.
- All MVHR systems currently on the UK market achieve boost ventilation rates which meet AD F requirements; however, they are not designed to achieve purge ventilation rates. In urban locations purge ventilation may not be possible by opening windows; therefore, the system may not be capable of maintaining thermal comfort in summer. The requirement that MVHR systems meet all the ventilation needs of energy efficient dwellings must be addressed and guidance produced on how this can be achieved.
- Filters commonly supplied with MVHR units in the UK are currently only F4. The suitability of such levels of filtration requires investigation, especially for urban dwellings. If higher levels of filtration are required, then the feedback to the occupant on filter condition and maintenance requirements needs to be very clear.
- The efficiency of fans and thermal heat exchangers has reached a level where there are only marginal gains still to be made. The next drive by the industry will be for advanced controls and in particular for demand controlled ventilation (DCV). If the energy savings resulting from the potential reduction in fan operation and heat loss are to be realised, the ‘building empty’ and ‘room empty’ minimum ventilation rates must be determined. It is vital that this is undertaken as a matter of urgency as systems are already being sold in the UK (in the refurbishment/ retrofit markets) that offer some level of demand control, and if there are health implications of reducing ventilation rates below those defined in AD F, then these need identifying and guidance produced on acceptable minima.
- Emissions from the materials used; research is required to ascertain whether or not product standards under development to meet requirements of the Construction Products Directive are adequate to achieve good IAQ in Code Level 4 to 6 homes. Also, should further controls be applied – as they are in Finland and Germany for example.

The following points should be considered and incorporated in studies of the performance of Code Level 4 to 6 buildings.

Established protocols (eg Crump et al., 2002 and international standards concerning indoor air in the ISO 16000 series) and previous studies of IAQ should be used as a guide to the parameters to be measured in an investigation of air quality in energy efficient homes.

Key parameters include:

- The performance of any MV equipment at installation and over 12 months of use (and preferably longer).
- The rate of air exchange, in different seasons and under a range of occupancy behaviour. This should be undertaken at background and boost ventilation rates. For instance, a small sample of dwellings should be monitored to assess use of fan speed controls over a short time period.
- Temperature.
- Humidity.

- Internally generated pollutants:
    - VOCs
    - formaldehyde
    - NO_2 and CO in homes with combustion appliances
    - particles (PM10); consideration should also be given to finer particles and ultrafines for research value
    - CO_2.
- Other outdoor and indoor generated pollutants: ozone, PAHs, SVOCs in dust.

Additional parameters may become significant as homes become aged:

- mites and mite allergen
- other allergens
- fungi and bacteria.

In particular locations where ground contaminants may be elevated:

- radon
- CO_2 and methane.

Where airflow rates have been found to have been lowered after commissioning by the occupants, the noise of the system should be investigated, while operating, and at the commissioned airflow rates.

Of great importance in association with any measurements, are records of occupants' activities (diaries) including in particular changing ventilation conditions and use of products in the home. The occupants' understanding and undertaking of maintenance on the system should be determined. Also the recording of the occupants' satisfaction with the indoor environment with respect to thermal comfort, perceived odour and freshness of the air, and of any occurrence of SBS type symptoms, should be undertaken.

Studies could focus only on highly energy efficient homes and evaluate the measurement data against available IAQ guidelines, but a more powerful approach would be to compare with a control group of homes that are less energy efficient than those built to Code Level 4 to 6.

Noting concerns about the poor performance of ventilation systems because of a lack of maintenance and misuse and interference by some occupants, an appropriate assessment of IAQ should not be limited to the first heating and summer season. If the performance of the systems deteriorates with time the risks associated with poor ventilation would be expected to appear to a greater extent in subsequent years.

8 Conclusion

Indoor air quality is determined by a range of pollutants generated indoors and outdoors. The pollutant load in the air entering the building may be modified by interactions with surfaces, and the resulting concentration forms a baseline to which pollutants are added from a wide range of indoor sources. Provided that the outdoor air is sufficiently clean, effective ventilation removes the indoor pollutants at a sufficient rate to maintain an appropriate air quality.

Ventilation also impacts on the maintenance of levels of temperature and humidity that are suitable for occupant comfort and wellbeing. These parameters can directly affect occupants' health or indirectly, eg by influencing the growth of mould and the proliferation of mites.

People spend the large majority of their time indoors and particularly in the home. Those most vulnerable to pollutants and other adverse environmental conditions such as the very young, the elderly and the sick may spend nearly all of their time indoors. Therefore IAQ is recognised as an important factor affecting the health and wellbeing of people and in response, organisations such as the WHO and the European Commission are developing guidance and policies to improve IAQ.

An important part of the international effort to reduce the possible future impact of climate change is to reduce CO_2 emissions by using less energy. There is significant potential to reduce energy used in buildings and initiatives such as the CSH have been introduced to drive forward an increase in the energy efficiency of new buildings. This is resulting in changes in construction practice whereby highly insulated and airtight structures are being designed and built with an expectation of a greater use of MVHR ventilation systems. This will have an impact on the quality of air in homes as well as other aspects of the internal environment, such as acoustics and daylight. There are associated risks of declining air quality, but also opportunities for improvement provided that appropriate measures are adopted.

Experience from other countries provides a useful insight into the likely construction practices that may be increasingly adopted in the UK. However, there are differences in climate, construction practice and the social and economic circumstances of occupants, and therefore direct transfer of knowledge is problematic. With regard to IAQ in particular there is a dearth of information relevant to highly energy efficient structures.

There is an urgent need for research into the performance of highly energy efficient homes with respect to the quality of the internal environment and the impact on the health and wellbeing of occupants. The following broad but inter-related topics require investigation.

- Performance of products and designs:
    - noise generated
    - ability to clean fans and ductwork
    - achievement of the required air supply
    - air filter efficiency
    - use of demand control ventilation
    - impact of chemical emissions from materials on IAQ.
- Performance of Code Level 4 to 6 homes.
    - performance of systems at installation, after one year of use, and beyond
    - evaluation of IAQ and ventilation in a representative sample of homes (temperature, RH, VOCs, formaldehyde, CO, NOx, particles, mites, bacteria, fungi, radon, ozone, SVOCs in dust, CO_2 and air exchange rate).

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APPENDIX A

Literature searches

Information sources

Online database searches have been undertaken on air quality, ventilation and health in homes. The following strategies have been used to access particular published scientific papers and journals for inclusion in the review.

Search terms and key words:

- air exchange rate
- air tight homes
- airtight homes
- air tightness in homes
- airtightness in homes
- bacteria/bacterial
- (the) Code for Sustainable Homes
- damp/dampness
- energy efficient homes
- formaldehyde
- fungi/fungus
- health effects
- highly insulated homes
- humidity/relative humidity
- IAQ
- indoor air pollutants
- indoor air quality
- indoor pollutants
- infiltration in homes
- insulated homes
- insulation in homes
- microbes/microbial
- occupant comfort
- organic compound/s
- semi-volatile organic compound/s
- VOC/s
- ventilation in homes
- volatile organic compound/s.

PubMed

The following search term was not found in PubMed:

- (the) Code for Sustainable Homes.

To get a rough idea of the number of results we would expect to find, the following terms and strings were searched for to begin with:

- energy efficient homes (15 hits)
- highly insulated homes OR insulated homes OR insulation in homes (49 hits)
- air tightness in homes OR air tight homes OR air-tight homes (9 hits)
- indoor air quality (7526 hits)
- indoor air pollutants (3220 hits).

Searches have been carried out using various combinations of search terms, the most effective of which are listed below.

Search 1 Energy efficient homes

- (indoor air quality OR IAQ OR indoor air pollutants OR indoor pollutants) AND (energy efficient homes)

This search generated six results.

Search 1 was then combined with the following strings:

- (VOC OR VOCs OR volatile organic compound OR volatile organic compounds OR semi-volatile organic compound OR semi-volatile organic compounds OR organic compound OR organic compounds OR formaldehyde)
- (health effects and occupant comfort)
- (dampness OR damp OR humidity OR relative humidity OR fungi OR fungus OR spores OR microbes OR microbial OR bacteria OR bacterial).

No new results were found when Search 1 was combined with these strings.

Search 2 Highly insulated homes

- (indoor air quality OR IAQ OR indoor air pollutants OR indoor pollutants) AND (highly insulated homes OR insulated homes OR insulation in homes)

This search generated 17 results.

Search 2 was then combined with the following strings:

- (VOC OR VOCs OR volatile organic compound OR volatile organic compounds OR semi-volatile organic compound OR semi-volatile organic compounds OR organic compound OR organic compounds OR formaldehyde).

This search generated 14 new results:

- (health effects and occupant comfort).

No new results were found as a result of combining Search 2 with this string.

- (dampness OR damp OR humidity OR relative humidity OR fungi OR fungus OR spores OR microbes OR microbial OR bacteria OR bacterial).

This search generated eight new results.

Search 3 Air tight homes

- (indoor air quality OR IAQ OR indoor air pollutants OR indoor pollutants) AND (air tightness in homes OR air tight homes OR air-tight homes)

This search generated eight results.

Search 3 was then combined with the following strings:

- (VOC OR VOCs OR volatile organic compound OR volatile organic compounds OR semi-volatile organic compound OR semi-volatile organic compounds OR organic compound OR organic compounds OR formaldehyde)
- (health effects and occupant comfort)
- (dampness OR damp OR humidity OR relative humidity OR fungi OR fungus OR spores OR microbes OR microbial OR bacteria OR bacterial).

No new results were found as a result of combining Search 3 with these strings.

Search 4 Ventilation in homes

The following searches did not generate any new results:

- (ventilation in homes) AND (energy efficient homes)
- (ventilation in homes) AND (highly insulated homes OR insulated homes OR insulation in homes)
- (ventilation in homes) AND (air tightness in homes OR air tight homes OR air-tight homes).

Search 5 Indoor pollutants

- (indoor air quality OR IAQ OR indoor air pollutants OR indoor pollutants) AND (ventilation in homes)

This search generated 141 results.

Search 6 Indoor air pollutants

- (indoor air quality OR IAQ OR indoor air pollutants OR indoor pollutants) AND (infiltration in homes)

This search generated 21 results.

Additional searches

This search generated 160 results:

- (indoor air quality OR IAQ OR indoor air pollutants OR indoor pollutants OR VOC OR VOCs OR volatile organic compound OR volatile organic compounds OR semi-volatile organic compound OR semi-volatile organic compounds OR organic compound OR organic compounds OR formaldehyde) AND (ventilation in homes OR energy efficient homes)

This search generated 164 results:

- (indoor air quality OR IAQ OR indoor air pollutants OR indoor pollutants OR health effects OR occupant comfort) AND (ventilation in homes OR energy efficient homes).

This search generated 188 results:

- (indoor air quality OR IAQ OR indoor air pollutants OR indoor pollutants OR dampness OR damp OR humidity OR relative humidity OR fungi OR fungus OR spores OR microbes OR microbial OR bacteria OR bacterial) AND (ventilation in homes OR energy efficient homes).

When all three searches were combined, 214 results were generated:

- (indoor air quality OR IAQ OR indoor air pollutants OR indoor pollutants OR health effects OR occupant comfort OR VOC OR VOCs OR volatile organic compound OR volatile organic compounds OR semi-volatile organic compound OR semi-volatile organic compounds OR organic compound OR organic compounds OR formaldehyde OR dampness OR damp OR humidity OR relative humidity OR fungi OR fungus OR spores OR microbes OR microbial OR bacteria OR bacterial) AND (ventilation in homes OR energy efficient homes).

In addition to databases, proceedings of recent conferences such as the tri-annual international series ‘Indoor Air’ and the ‘Healthy Buildings’ series were examined as well as recent editions of the main journals in the field such as ‘Indoor Air’. Use was also made of contacts in the UK and abroad, particularly those involved with European research and network projects and serving on standardisation committees relevant to IAQ. Information was also obtained from a range of internet sites.

APPENDIX B

CLG sponsored study on ventilation and air quality in new homes

This study aims to monitor ventilation and IAQ in airtight homes constructed to the 2006 edition of Parts F and L of the Building Regulations. It is being undertaken to investigate the effectiveness of current guidance in AD F.

It is planned to monitor approximately 20 naturally ventilated dwellings all with an air permeability better than 10 $m^3/h/m^2$, with the sample biased such that half achieve approximately 5 $m^3/h/m^2$ or better. An initial pilot exercise involving two homes preceded the main study, that is to have taken place during spring 2009.

The focus of this study is to determine whether the ventilation capacity is sufficient, and therefore occupants will be instructed on the use of the available ventilation provisions and requested to use them appropriately. Therefore the intention is that trickle-vents will be fully open unless occupants have problems, and extract fans and cooker hoods operated at their highest settings when cooking and bathing. The adequacy of installation and commissioning of the extract fans and cooker hoods will be assessed and any faults found notified to the owner.

In addition to airtightness the following are monitored over a 1 week period:

- outdoor as well as the indoor air temperature and RH in key rooms
- mean NO_2 concentrations in the kitchen and outside.
- mean total VOC and formaldehyde concentrations in rooms most likely to have highest levels, as well as outside
- CO_2 will be measured in the master bedroom of selected homes
- mean air exchange rate using a perfluorocarbon tracer gas method
- activities of occupants through completion of questionnaires and diaries.

The results will be used to assess the effectiveness of the current ventilation guidance in AD F to control IAQ to guideline concentrations given in Appendix A of AD F.

APPENDIX C

Example: Code for Sustainable Homes in the UK

In addition to the homes on the BRE Innovation Park referred to in the main body of the report, other examples of homes built according to the CSH include those described by CLG (2009a) and BASF (2008).

The Good Homes Alliance reported on progress with researching and developing case studies on some of the first CSH homes built in the UK (CLG, 2009a). Four projects are described that are small-scale sites consisting of between two and 22 properties and a range of building types: detached and terraced homes, flats and apartments and live–work units.

The sites represent a range of building systems and construction processes:

- timber frame with OSB cassettes
- timber frame with a cavity wall cement particle board outer sheath and brick external cladding
- timber frame with a cavity wall of concrete external block and insulating internal block
- timber frame with prefabricated solid cross timber laminated panels and external insulation
- structural insulated panel system (SIPS) with additional insulation.

Among the key lessons learnt is that the CSH can be used on a wide range of building types, from flats/apartments through to large detached dwellings. Four case studies are described:

- A development of five private housing units in Somerset due for completion in 2009. Construction used offsite manufactured timber and OSB cassettes. Insulation between timber studs was by recycled newspaper and the external insulation was comprised of wood fibre boards. Sheep wool was used for inter-floor insulation. The homes were required to meet Code Level 5. Plans were in place for post-occupancy monitoring, but this is not detailed in the report (CLG, 2009a).
- A development of nine, three storey live–work units in Bristol. Construction used prefabricated solid cross timber laminated panels with external insulation and render. The roof was an aluminium sheet system and the ground floor was a concrete slab, with foamed sheet insulation and a raised timber floor. An MVHR system was used incorporating a heating coil for space heating. None of the properties were occupied at the time of writing this review.
- A development of nine houses constructed for a housing association in Staffordshire in 2007. Built to Code Level 3, they are constructed using a factory-fabricated timber frame with particle board sheathing and brick cladding. Phenolic foam was injected into the external wall void and this was supplemented by cut rigid foam insulation. The floors were a concrete beam system incorporating polystyrene infill and with a concrete screed. The dwellings are occupied and the occupant of one home was interviewed; they commented that the house was draught-free in comparison with previous accommodation, that it allowed for fresh air by opening windows and had good acoustic properties.
- A development of two, two-bedroom flats in Surrey planned originally to achieve Code Level 3, but which eventually achieved Code Level 5. It was constructed using SIPS and beam and block flooring with mineral wool and expanded polystyrene insulation. The base model specification used was similar to the PassivHaus.

  An MVHR system was installed and a home user guide was provided about how to operate the renewable energy and ventilation systems. It is reported that the residents were generally satisfied with the development, but had problems with the operation of the biomass boiler system.

The BASF project has been built as part of the Creative Energy Homes Project at the University of Nottingham to demonstrate how BASF raw materials can be used to create an energy efficient and affordable home. The house is designed to exceed Code Level 4 and comply with the PassivHaus standard for annual heating load. It is based on passive solar design with highly insulated north, east and west aspect walls and a fully glazed south aspect with a ‘sun space’. A ground air heat exchanger draws outside air through an underground network of pipes and either preheats the air in winter or precools the air in summer. A SIPS construction is used and the sandwich panels contain rigid polyurethane foam. Enhanced natural ventilation is achieved by mechanically opening vents below the roof ridge level. To assist with thermal regulation indoors, a modified plasterboard material has been used internally. Microscopically small polymer spheres containing wax undergo phase changes on heating and cooling. The ability of the spheres to store and release heat provides an active system of temperature management.

APPENDIX D

PassivHaus

The following information, taken from the web site www.europeanpassivehouses.org, provides some further details regarding the PassivHaus standard.

Energy performance

A PassivHaus home's heating power demand is very low, on normal winter days only 10 W/m^2. The requirement to fulfil this goal is to reduce the building heat losses to a minimum. To accomplish the low heat losses, quality of design and construction needs to be high. A PassivHaus home's thermal insulation level is well beyond typical buildings. As the concept is not widely adopted, and as there is lack of experience available to build PassivHaus homes in most countries, guidance in all the procurement phases is needed, especially at the site.

PassivHaus homes can be heated using ventilation heating systems. This is also a relatively rare way of heating. Thus the building users need to be informed on the performance and limitations and control of the system. If the user's expectations are different, the delivery may not fulfil their demand. Poor understanding of the systems and the concept may contribute to problems in use, and also increased energy consumption.

It is essential that the inhabitants are informed properly about the characteristics and important factors affecting energy use and indoor climate of a PassivHaus homes. An informative meeting and a guide book to inhabitants is strongly encouraged.

Procurement

To achieve a high standard of energy-efficiency for a building requires more effort in planning and design phases, and in construction compared to standard practice. Once experience increases, the effort reduces. Integrated design processes help achieve the desired outcome. As the heating energy consumption and power demand are extremely low, even small defects in the design and construction may reduce the possibilities of reaching the target.

Continuous site checks and quality control are essential during the whole building process. On the building site both visual inspections and measurements should be carried out before inhabitants move in. The PassivHaus certification scheme lays down the requirements for commissioning, whereas the PassivHaus Planning Package (PHPP) is mainly used as a design verification tool. The most important test is the airtightness test using the blower door test.

The procurement process should fulfil user and owner requirements and PassivHaus performance requirements. These requirements should guide the whole design and construction process. The following steps are crucial for the outcome:

Pre-design phase:

- commitment to PassivHaus concept
- spatial planning requirements for architectural design
- site characteristics, wind rose, ground conditions
- building type, materials and systems.

Design:

- utilisation of PassivHaus certification schemes
- selection of building envelope components
- selection of heating and ventilation systems
- trade-offs: floor plans and volume-surface factor
- compensation for heat losses from poor compactness

- design auditing: PH certification.

Design co-operation:

- requirements for spatial planning, space allocation for HVAC equipment and routing for HVAC installations
- avoidance of unnecessary thermal bridging
- performance of heating system with regard the thermal properties of the building envelope
- designers' solutions for whole building performance.

Construction:

- performance-based bidding, ie decision making based on performance, quality, delivery etc
- selection of contractors: commitment, experience, references.

Commissioning:

- equipment testing
- airtightness tests
- balancing of the ventilation system
- energy consumption after one year of use.

Maintenance:

- user instructions
- maintenance manual.

A further web site (www.passivhaus.org.uk/index.jsp?id=667) provides information directed to constructing a PassivHaus dwelling in the UK. Some information from that site follows.

A dwelling which achieves the PassivHaus standard typically includes:

- very good levels of insulation with minimal thermal bridges
- well thought out utilisation of solar and internal gains
- excellent level of airtightness
- good IAQ, provided by a whole-house MV system with highly efficient heat recovery.

By specifying these features the design heatload is limited to the load that can be transported by the minimum required ventilation air. Thus, a PassivHaus does not need a traditional heating system or active cooling to be comfortable to live in – the small heating demand can be typically met using a compact services unit which integrates heating, hot water and ventilation in one unit (although there are a variety of alternative solutions).

For Europe (40 to 60° Northern latitudes), a dwelling is deemed to satisfy the PassivHaus criteria if:

- the total energy demand for space heating and cooling is less than 15 kWh/m^2/yr treated floor area
- the total primary energy use for all appliances, domestic hot water and space heating and cooling is less than 120 kWh/m^2/yr.

These figures are verified at the design stage using the PHPP. It is also essential to follow a quality control procedure to avoid onsite problems which may prevent excellent levels of airtightness and thermal insulation being achieved.

Outline specification for a PassivHaus in the UK

The information in the following table is for guidance only, compliance with the PassivHaus standard must be assessed using the PHPP.

	PassivHaus standard	**UK new build common practice**
Compact form and good insulation	All components of the exterior shell of a PassivHaus are insulated to achieve a U-value that does not exceed 0.15 $W/m^2/K$	Limiting U-values of approximately 0.25 to 0.35 $W/m^2/K$
Southern orientation and shade considerations	Passive use of solar energy is a significant factor in PassivHaus design	Some consideration is given with regard to north/south orientation, but the improved energy savings resulting from passive site design are often overlooked
Energy-efficient window glazing and frames	Windows (glazing and frames, combined) should have U-values not exceeding 0.80 $W/m^2/K$, with solar heat-gain coefficients around 50%*	1.8 to 2.2 W/m^2K typical
Building envelope airtightness	Air leakage through unsealed joints must be less than 0.6 times the house volume per hour (this is the equivalent of an air permeability value of less than 1 $m^3/h/m^2$ @ 50 Pa)	Design air permeability of 7 to 10 $m^2/h/m$ at 50 Pa. This is approximately a factor of 10 poorer than the PassivHaus standard. Research has also shown that air permeability values for completed dwellings frequently exceed these design limits
Passive preheating of fresh air	Fresh air may be brought into the house through underground ducts that exchange heat with the soil. This preheats fresh air to a temperature above 5°C (41°F), even on cold winter days	The majority of new-builds do not achieve good enough air permeability values to warrant the incorporation of a whole house ventilation system – thus trickle-vents, extract fans, or passive stack ventilation is commonly used
Highly efficient heat recovery from exhaust air using an air-to-air heat exchanger	Most of the perceptible heat in the exhaust air is transferred to the incoming fresh air (heat recovery rate over 80%)	
Energy-saving household appliances	Low energy refrigerators, stoves, freezers, lamps, washers, dryers, etc are indispensable in a PassivHaus	Dedicated low-energy lights are provided in a number of rooms in a new dwelling – if appliances are supplied they will be generally C-rated or perhaps 'Energy Saving Recommended' in some instances (as these are widely available)
Total energy demand for space heating and cooling	Less than 15 $kWh/m^2/yr$	Typically 55 $kWh/m^2/yr$

* The Solar Heat Gain Co-efficient (SHGC) is provided as a guide, it can be adjusted for glazing on different façades. This can help either reduce heat loss on sheltered sides/north facing glazing, or alternatively help to reduce the likelihood of overheating when specified in conjunction with other features/strategies (please note that the SHGC of a window usually decreases as the U-value improves).

APPENDIX E

Canadian R-2000™ homes

This information is adapted from text contained in internet sources (http://r2000.chba.ca and www.envirohome.chba.ca).

R-2000™ homes are described as the most energy-efficient and environmentally responsible new homes on the Canadian market. They are built to demanding standards for energy efficiency and IAQ and are backed by a quality assurance process that is certified by the government of Canada. Some features are as follows.

Energy efficiency

The R-2000™ standard is based on energy targets, that is, the maximum amount of energy that a home is allowed to use for space and water heating. The target varies according to geographical location, size and fuel type. Standard operating conditions are used in the calculations for other variables, such as lighting, appliance and interior loads.

R-2000™ builders meet the energy target by using superior construction techniques and high quality products. This includes lots of insulation, careful sealing to eliminate air leaks and drafts, and energy-efficient heating, cooling and ventilation equipment.

R-2000™ builders take advantage of solar heating by placing homes on the development site to maximise the amount of sun coming into the home in the winter. Roof overhangs, awnings and strategic plantings (trees and shrubs) are used to keep the home cool in the summer. Windows must have a minimum energy rating value, depending on whether they are openable or fixed.

Typically, the air leakage allowed is only half of that in other new homes; older homes often have 10 times as much air leakage. And typically, an R-2000™ home uses 30 to 40% less energy than a comparable non-R-2000™ home. The R-2000™ target is a minimum target – depending on construction methods and equipment chosen, this performance may be exceeded.

Indoor air quality

The homes are designed and built to protect the quality of the living environment and the occupants' health. R-2000™ takes a systematic approach to improved air quality and a healthier home.

Ventilation

An important key to good IAQ is ventilation – getting rid of moisture and stale air and replacing it with fresh air from the outside. Most R-2000™ homes use a whole-house MV system, called an HRV, that brings fresh filtered air to every room and removes stale air, excess humidity, pollutants and odours. The air in the home is replaced with fresh outdoor air about eight times a day. Further ventilation can be achieved by opening windows.

Construction

Careful air-sealing of the exterior walls helps to keep dust, pollen and other outdoor pollutants out and reduces the noise coming in from the outside. Because it is performance based, the standard allows a wide range of construction types: traditional wood framing, steel framing, insulated concrete forms, or any other kind of framing materials, with any type of exterior cladding being possible.

During construction, R-2000™ builders are careful to not introduce pollutants into the home. Products that emit chemicals are kept to a minimum, such as alkyd paints, formaldehyde-bonded particle-board, solvent-based glues and carpeting. The builder is required to select healthier building components, eg water-based paints and finishes, sealed wood products, hardwood flooring, linoleum, ceramic tile and carpeting that give off fewer chemicals. Hard-surface flooring has the added advantage of being easy to keep clean and free of dust mites, which have been linked to allergies.

Equipment

The R-2000™ standard addresses the risk of exposure of occupants to combustion gases by setting rigid requirements for the venting of combustion equipment. In addition, a CO detector is installed in all homes with combustion appliances or an attached garage.

The R-2000™ certificate

Every R-2000™ home is certified. Issued by the government of Canada, the certificate is proof that the home has met the R-2000™ quality assurance requirements. Once an R-2000™ home is completed, the builder submits an application stating the home meets all of the R-2000™ requirements for certification. Homeowners receive a numbered R-2000™ certificate for their records and an R-2000™ label which is attached to the electrical panel in the home. A registry of certified R-2000™ homes is maintained by Natural Resources Canada and by R-2000™ regional delivery agents.

APPENDIX F

US EPA Indoor airPLUS and Energy Star Program

The US Environmental Protection Agency created the Indoor airPLUS new home label to help builders meet the growing consumer preference for homes with improved IAQ. It is a complementary label to the Energy Star for new homes. Further details are available from the web site: www.epa.gov/indoorairplus, which includes four brochures available for download; one of these – Indoor airPLUS Construction Specifications (Ref: EPA 402/K-08/003, January 2009) – is reproduced in this Appendix by kind permission of US EPA.

These specifications provide the measures builders can take to help improve indoor air quality in new homes compared with homes built to minimum code. Homes that comply with these specifications qualify as Indoor airPLUS homes. This is an essential document for builders designing Indoor airPLUS homes.

EPA
United States
Environmental Protection
Agency

Indoor airPLUS
CONSTRUCTION SPECIFICATIONS

Indoor Air Quality (IAQ)

About the Indoor airPLUS Construction Specifications

These specifications were developed by the U.S. Environmental Protection Agency (EPA) to recognize new homes equipped with a comprehensive set of Indoor Air Quality (IAQ) features. They were developed with significant input from stakeholders, based on best available science and information about risks associated with IAQ problems, and balanced with practical issues of cost, builder production process compatibility, and verifiability. Although these measures were designed to help improve IAQ in new homes compared with homes built to minimum code, they alone cannot prevent all IAQ problems. Occupant behavior is also important. For example, smoking indoors would negatively affect IAQ and the performance of the specified Indoor airPLUS measures. For more information, visit **epa.gov/indoorairplus**.

How to Qualify a Home for the Indoor airPLUS Label

Homes that comply with these specifications and are verified with a completed Indoor airPLUS Verification Checklist can use Indoor airPLUS as a complementary label to ENERGY STAR for New Homes. ***Only ENERGY STAR qualified homes are eligible for this label.*** Verification can be completed during the ENERGY STAR inspection process, and must be conducted in accordance with Residential Energy Services Network (RESNET) Standards by a RESNET-accredited provider and must meet all applicable codes. Instructions for Indoor airPLUS verification are on the back page of the Verification Checklist.

Qualified homes earn the Indoor airPLUS label. Place it next to the ENERGY STAR label.

Terms Used in This Document

- **EXCEPTIONS** to the requirements described in these construction specifications are noted as appropriate. For climate exceptions, refer to the 2006 International Energy Conservation Code (IECC) Climate Zone map (Figure 301.1) on the inside back cover. Climate Zone names may include a number for the temperature zone and a letter for the moisture zone (e.g., Zone 3C refers to coastal California only).
- **NOTES** provide additional information to clarify specification requirements.
- **ADVISORIES** provide additional guidance to be considered, but are not specification requirements.
- **ABBREVIATIONS** and **REFERENCES** used in these specifications are listed on pages 8 to 10.
- **PERFORMANCE TEST ALTERNATIVES** describe alternate compliance approaches where performance testing is practical and results are comparable to those of the prescriptive best practices required in the specification.

Table of Contents

EPA
United States
Environmental Protection
Agency

Indoor airPLUS Verification Checklist

Address or Div/Lot#:

City/State/Zip: **Date:**

Section		Requirements (see Indoor airPLUS Construction Specifications for details)	N/A	Verified by Builder	 Rater
Moisture Control		**Water-Managed Site and Foundation**			
	1.1	Site & foundation drainage: sloped grade, protected drain tile, & foundation floor drains		☐	☐
	1.2	Capillary break below concrete slabs & in crawlspaces (Exception - see specification)	☐	☐	☐
	1.3	Foundation wall damp-proofed or water-proofed (Except for homes without below-grade walls)	☐	☐	☐
	1.4	Basements/crawlspaces insulated & conditioned (Exceptions - see specification)	☐	☐	☐
		Water-Managed Wall Assemblies			
	1.5	Continuous drainage plane behind exterior cladding, properly flashed to foundation		☐	☐
	1.6	Window & door openings fully flashed		☐	☐
		Water-Managed Roof Assemblies			
	1.7	Gutters/downspouts direct water a minimum of 5' from foundation (Except in dry climates)	☐	☐	☐
	1.8	Fully flashed roof/wall intersections (step & kick-out flashing) & roof penetrations		☐	☐
	1.9	Bituminous membrane installed at valleys & penetrations (Except in dry climates)	☐	☐	☐
	1.10	Ice flashing installed at eaves (Except in Climate Zones 1 - 4)	☐	☐	☐
		Interior Water Management			
	1.11	Moisture-resistant materials/protective systems installed (i.e., flooring, tub/shower backing, & piping)			☐
	1.12	No vapor barriers installed on interior side of exterior walls with high condensation potential		☐	☐
	1.13	No wet or water-damaged materials enclosed in building assemblies		☐	☐
Radon	2.1	Approved radon-resistant features installed (Exception - see specification)	☐	☐	☐
	2.2	Two radon test kits & instructions/guidance for follow-up actions provided for buyer (Advisory-see specification)	☐	☐	☐
Pests	3.1	Foundation joints & penetrations sealed, including air-tight sump covers			☐
	3.2	Corrosion-proof rodent/bird screens installed at all openings that cannot be fully sealed (e.g., attic vents)		☐	☐
HVAC	4.1	HVAC room loads calculated, documented; system design documented; coils matched			☐
	4.2	Duct system design documented & properly installed OR duct system tested (check box if tested) ☐	☐		☐
	4.3	No air handling equipment or ductwork installed in garage; continuous air barrier required in adjacent assemblies			☐
	4.4	Rooms pressure balanced (using transfer grills or jump ducts) as required OR tested (check box if tested) ☐	☐		☐
	4.5	Whole house ventilation system installed to meet ASHRAE 62.2 requirements			☐
	4.6	Local exhaust ventilation to outdoors installed for baths, kitchen, clothes dryers, central vacuum system, etc.			☐
	4.7	Central forced-air HVAC system(s) have minimum MERV 8 filter, no filter bypass, & no ozone generators			☐
	4.8	Additional dehumidification system(s) or central HVAC dehumidification controls installed (In warm-humid climates only)	☐		☐
Combustion Pollutants		**Combustion Source Controls**			
	5.1	Gas heat direct vented; oil heat & water heaters power vented or direct vented (Exceptions - see specifications)	☐		☐
	5.2	Fireplaces/heating stoves vented outdoors & meet emissions/efficiency standards/restrictions	☐		☐
	5.3	Certified CO alarms installed in each sleeping zone (e.g., common hallway) according to NFPA 720			☐
	5.4	Smoking prohibited in common areas; outside smoking at least 25' from building openings (Multi-family homes only)	☐	☐	☐
		Attached Garage Isolation			
	5.5	Common walls/ceilings (house & garage) air-sealed before insulation installed; house doors gasketed & closer installed	☐		☐
	5.6	Exhaust fan (minimum 70 cfm, rated for continuous use) installed in garage & vented to outdoors (controls optional)	☐		☐
Materials	6.1	Certified low-formaldehyde pressed wood materials used (i.e., plywood, OSB, MDF, cabinetry)		☐	☐
	6.2	Certified low-VOC or no-VOC interior paints & finishes used		☐	☐
	6.3	Carpet, adhesives, & cushion qualify for CRI Green Label Plus or Green Label testing program	☐	☐	☐
Final	7.1	HVAC system & ductwork verified dry, clean, & properly installed			☐
	7.2	Home ventilated before occupancy OR initial ventilation instructions provided for buyer		☐	☐
	7.3	Completed checklist & other required documentation provided for buyer		☐	☐

Rater/Provider: **Builder:**

Company: **Company:**

Signature: **Signature:**

Guidance for Completing the Indoor airPLUS Verification Checklist:

1. Only ENERGY STAR qualified homes verified to comply with these specifications can earn the Indoor airPLUS label. See Indoor airPLUS Construction Specifications for full descriptions of the requirements, terms, exceptions, abbreviations, references, and climate map used in this checklist. Verification is not complete until this checklist is completed in full and signed.
2. Check one box per line. Check "N/A" for specifications that do not apply for specific conditions (e.g., climate) according to the Exceptions described in the Indoor airPLUS Construction Specifications. Check either "Builder" or "Rater" for all other items to indicate who verified each item. Items may be verified visually on site during construction, by reviewing photographs taken during construction, by checking documentation, or through equivalent methods as appropriate. If using a performance testing alternative to meet requirement 4.2 or 4.4, the box marked "Tested" must be checked and testing documentation must be provided in the Home Energy Rating System/Builder Option Package (HERS/BOP) file.
3. The rater who conducted the verification, or a responsible party from the rater's company, must sign the completed verification checklist. The builder must sign the checklist if any items in the "Builder" column are checked, and by so doing accepts full responsibility for verifying that those items meet Indoor airPLUS requirements.
4. The builder provides one copy of the completed and signed checklist for the buyer. The HERS/BOP provider or rater files a copy with HERS/BOP and ENERGY STAR documentation (e.g., Thermal Bypass Checklist) for the home.
5. The checklist may be completed for a batch of homes using a RESNET-approved sampling protocol when qualifying homes as ENERGY STAR. For example, if the approved sampling protocol requires rating one in seven homes, then the checklist will be completed for the one home that was rated.

Note: The Indoor airPLUS Construction Specifications are designed to help improve indoor air quality (IAQ) in new homes compared with homes built to minimum code. These measures alone cannot prevent all IAQ problems; occupant behavior is also important. For example, smoking indoors would negatively impact a home's IAQ and the performance of the specified Indoor airPLUS measures.

Notes:

For further information on the Indoor airPLUS program, visit epa.gov/indoorairplus.

EPA Indoor airPLUS QUALIFIED HOME

Qualified homes earn the Indoor airPLUS label. Place it next to the ENERGY STAR label.

ENERGY STAR

All Indoor airPLUS qualified homes meet strict guidelines for energy efficiency set by ENERGY STAR, the nationally-recognized symbol for energy efficiency.

Indoor airPLUS Construction Specifications

1. Moisture Control

Note:
ENERGY STAR Thermal Bypass Checklist (TBC) requirements are an integral part of the Indoor airPLUS moisture control strategy. TBC requirements improve the control of air and thermal flows through building assemblies, which is critical to controlling water vapor migration and condensation. Since TBC compliance and verification are required for ENERGY STAR qualification, TBC requirements are not re-stated in the Indoor airPLUS Construction Specifications.

Water-Managed Site and Foundation

1.1 Provide site and foundation drainage as follows:

- Slope patio slabs, walks and driveways a minimum of ¼ in. per ft. away from house, tamp back-fill to prevent settling, AND slope the final grade away from the foundation at a rate of ½ in. per ft. over a minimum distance of 10 ft. Where setbacks limit space to less than 10 ft., provide swales or drains designed to carry water away from the foundation. Back-fill tamping is not required if proper drainage can be achieved using non-settling compact soils, as determined by a certified hydrologist, soil scientist, or engineer.
- Install protected drain tile at the footings of basement and crawlspace walls, level or sloped to discharge to outside grade (daylight) or to a sump pump. The top of each drain tile pipe must always be below the bottom of the concrete slab or crawlspace floor. Each pipe shall be surrounded with at least 6 inches of ½ to ¾ in. washed or clean gravel. The gravel layer shall be fully wrapped with fabric cloth to prevent fouling of the drain tile. If a drain tile discharges to daylight and radon-resistant features are required (see Specification 2.1), install a check valve at the drain tile outfall.
- Install a drain or sump in basement and crawlspace floors, discharging to daylight at least 10 ft. outside the foundation or into an approved sewer system. Floor drains are not required for slab-on-grade foundations.

1.2 Install capillary breaks as follows:

Beneath concrete slabs, including basement floors:

- Install a 4 in. layer of ½ in. diameter or greater clean aggregate, covered with 6 mil (or thicker) polyethylene sheeting, overlapped 6 to 12 in. at the seams, and in direct contact with the concrete slab above; OR
- Install a 4 in. uniform layer of sand, overlain with a layer or strips of geotextile drainage matting installed according to the manufacturer's instructions, and covered with polyethylene sheeting overlapped 6 to 12 in. at the seams.

Crawlspace floors:

- Cover crawlspace floors with a concrete slab over 6 mil (or thicker) polyethylene sheeting overlapped 6 to 12 in. at the seams; OR
- Cover crawlspace floors with 6 mil polyethylene (10 mil recommended) sheeting, overlapped 6 to 12 in. and sealed or taped at the seams and penetrations. The sheeting shall be attached to walls and piers with adhesive and furring strips.

Exceptions:

- In areas of free-draining soils—identified as Group 1 by a certified hydrologist, soil scientist, or engineer through a site visit—a gravel layer or geotextile matting is not required under concrete slabs.
- Polyethylene sheeting is not required in Dry (B) climates, as defined by IECC Figure 301.1, unless the sheeting is required for radon resistance (see Specification 2.1).

1.3 Damp-proof or waterproof exterior surfaces of below-grade foundation walls as follows:

- Poured concrete, concrete masonry, and insulated concrete forms (ICFs) shall be finished with a damp-proof coating; AND
- Wood-framed walls shall be finished with trowel-on mastic and polyethylene, or with other waterproofing demonstrated to be equivalent.

Exceptions:

Houses without below-grade walls.

1.4 Insulate and condition basements and crawlspaces as follows:

- Insulate crawlspace and basement perimeter walls according to IRC Table N1102.1 or IECC Table 402.1.1 (also see Specification 1.12); AND
- Seal crawlspace and basement perimeter walls to prevent outside air infiltration; AND
- Provide conditioned air at a rate not less than 1 cfm per 50 s.f. of horizontal floor area. If radon-resistant features are required (see Specification 2.1), do not install exhaust ventilation, as described in IRC section R408.3.2.1.

Exceptions:

- Homes built in areas designated as flood zones (conditioned crawlspaces are not recommended for use in flood zones).
- Raised pier foundation with no walls.
- Dry climates, as defined by IECC Figure 301.1.
- Marine climates, as defined by IECC Figure 301.1, if no air handler or return ducts are installed in the crawlspace.

Note:

In each of the preceding exceptions, floors above unconditioned spaces shall be insulated to the IECC-specified R-value and sealed to prevent air infiltration.

Water-Managed Wall Assemblies

1.5 Install a continuous drainage plane behind exterior wall cladding, AND install flashing or an equivalent drainage system at the bottom of exterior walls to direct water away from the drainage plane and foundation. Drainage plane material shall overlap flashing and shall be fully sealed at all penetrations. Any of the following systems meet this requirement:

- Monolithic weather-resistant barriers (i.e., house wrap), shingled at horizontal joints and sealed or taped at all joints; OR
- Weather-resistant sheathings (e.g., faced rigid insulation), fully taped at all “butt” joints; OR
- Lapped shingle-style building paper or felt.

Note:

Include weep holes for masonry veneer and weep screed for stucco cladding systems, according to the manufacturer’s specifications.

1.6 Fully flash all window and door openings, including pan flashing at sills, side flashing that extends over pan flashing, and top flashing that extends over side flashing.

Water-Managed Roof Assemblies

1.7 Direct roof water away from the house using gutters and downspouts that empty into lateral piping that deposits water on a sloping finish grade a minimum of 5 ft. from the foundation. Roofs designed without gutters are acceptable if they are designed to deposit rainwater to a grade-level rock bed with waterproof liner and drain pipe that deposits water on a sloping finish grade, as specified above. When lot space limits or prevents required grading, direct roof water to an underground catchment system (not connected to the foundation drain system) that deposits water a minimum of 10 ft. from the foundation. Rainwater-harvesting systems may be used to meet this requirement when they are designed to properly drain overflow, meeting discharge-distance requirements above.

Exception:

Dry climates, as shown in IECC Figure 301.1.

1.8 Fully flash roof/wall intersections and all roof penetrations. Install step flashing at all roof/wall intersections, except metal and rubber membrane roofs, where continuous flashing should be installed. “Kick-out” flashing shall be installed at the low end of roof/wall intersections to direct water away from walls, windows, and doors below. In all cases, flashing shall extend at least 4 in. on the wall surface above the roof deck and shall be integrated with the drainage plane above (shingle style) to direct water onto and not behind flashing. In addition, intersecting wall siding should terminate a minimum of 1 in. above the roof, or higher according to the manufacturer’s recommendations.

1.9 Install self-sealing bituminous membrane or the equivalent at all valleys and roof decking penetrations for durability at potential failure points.

Exception:

Dry climates, as shown in IECC Figure 301.1.

1.10 In colder climates (IECC Climate Zones 5 and higher), install self-sealing bituminous membrane or the equivalent (“ice flashing”) over the sheathing at eaves to provide protection from ice dams. The ice flashing shall extend up the roof plane from the eave to a point at least 2 ft. inside the vertical plane of the exterior wall.

Exception:

Climate Zones 1 to 4, as shown in IECC Figure 301.1.

Interior Water Management

1.11 Install moisture-resistant materials and moisture-protective systems in vulnerable areas. For example:

- Install water-resistant hard-surface flooring in kitchens, bathrooms, entryways, laundry areas, and utility rooms. Do not install wall-to-wall carpet adjacent to toilets and bathing fixtures (i.e., tubs and showers).
- Install moisture-resistant backing material (i.e., cement board or the equivalent, but not paper-faced wall board) behind tub and shower enclosures.
- Install all condensate discharge according to IRC section M1411.3.
- Insulate piping installed in exterior walls.

1.12 ***Do not install continuous vapor barriers on the interior side of exterior walls that have high condensation potential (e.g., below-grade exterior walls in most climates and above-grade exterior walls in warm-humid climates).*** For the purpose of this specification, vapor barriers are materials that have a perm rating of 0.1 or less (see manufacturer's product specifications or 2005 ASHRAE Handbook of Fundamentals, Chapter 25, Tables 7A and 7B).

1.13 ***Do not install building materials that have visible signs of water damage or mold.*** In addition, interior walls shall not be enclosed (e.g., with drywall) if either the framing members or insulation has a high moisture content. For wet-applied insulation, follow the manufacturer's drying recommendations.

Advisory:
Lumber should not exceed 18% moisture content.

2. Radon Control

2.1 ***Homes built in EPA Radon Zone 1 (see epa.gov/radon/zonemap.html) shall be constructed with approved radon-resistant features according to EPA Building Radon Out; NFPA 5000, Chapter 49; IRC, Appendix F; CABO, Appendix F; or ASTM E1465.*** The following requirements shall be verified:

- Capillary break installed according to Specification 1.2; AND
- A 3 or 4 in. diameter gas-tight vertical vent pipe, clearly labeled "Radon Pipe" or "Radon System," connected to an open T-fitting in the aggregate layer (or connected to geotextile drainage matting according to the manufacturer's instructions) beneath the polyethylene sheeting, extending up through the conditioned spaces and terminating a minimum of 12 in. above the roof opening. For crawlspaces, install at least 5 ft. of horizontal perforated drain tile on either side of the T-fitting, attached to the vertical radon vent pipe beneath the sheeting and running parallel to the long dimension of the house; AND
- Radon fan installed in the attic (i.e., an active system) OR an electrical receptacle installed in an accessible attic location near the radon vent pipe (i.e., a passive system) to facilitate future fan installation if needed; AND
- Foundation air sealing with polyurethane caulk or the equivalent at all slab openings, penetrations, and control or expansion joints. Sump covers also shall be air sealed (e.g., mechanically attached with full gasket seal or equivalent.)

Exception:
The Indoor airPLUS Construction Specifications recommend, but do not require, radon-resistant features for homes built in EPA Radon Zones 2 and 3 unless required by local building codes (see Advisory 1).

Advisories:

1. Elevated levels of radon have been found in homes built in all three zones on EPA's Map of Radon Zones. Consult your state's radon coordinator for current information about radon in your area. Go to epa.gov/iaq/whereyoulive.html and click on your state for contact information.
2. If soil or groundwater contamination is suspected on or near the building site (e.g., former industrial sites), volatile contaminants or breakdown products may pose an IAQ risk through soil gas intrusion. In such cases, EPA recommends radon-resistant features consistent with Specification 2.1, which can prevent the intrusion of soil vapor into a house. See the EPA Vapor Intrusion Primer or ASTM E2600 for more information, or consult your state or tribal brownfield voluntary cleanup program or environmental regulatory agency for information on the risks of vapor intrusion in your area.

2.2 ***Provide two radon test kits designed for 48-hour exposures for the buyers of homes in EPA Radon Zones 1 and 2, including test kit instructions and EPA guidance on follow-up actions to be taken in response to the test results.***

Advisory:
The U.S. Surgeon General and EPA recommend that all homes (including homes built in Radon Zone 3) be tested for radon. Refer interested buyers to epa.gov/radon/ for more information.

3. Pest Barriers

3.1 ***Minimize pathways for pest entry by sealing penetrations and joints in and between the foundation and exterior wall assemblies with blocking materials, foam, and polyurethane caulk or the equivalent.*** Sump pit covers shall be air sealed (e.g., mechanically attached with full gasket seal or the equivalent).

Advisories:

1. Additional precautions should be taken in areas of "Heavy" termite infestation probability (as identified by IRC Figure 301.2[6]) as follows:
   - Foundation walls should be solid concrete or masonry with a top course of solid block, bond beam, or concrete-filled block; AND

- Interior concrete slabs should be constructed with 6 x 6 in. welded wire fabric or the equivalent, and concrete walls should be constructed with reinforcing rods to reduce cracking; AND
- Sill plates should be made of preservative-treated wood.

2. The following additional precautions should be taken in areas of "Very Heavy" termite infestation probability (as identified by IRC Figure 301.2[6]) i.e., Alabama, Florida, Georgia, Louisiana, Mississippi, South Carolina, and parts of California and Texas:

Below-grade:

- Foam plastic insulation should not be installed on the exterior face of below-grade foundation walls or under slabs.

Above-grade:

- Foam plastic insulation installed on the exterior of above-grade foundation walls should be kept a minimum of 6 in. above the final grade and any landscape bedding materials, and should be covered with moisture-resistant, pest-proof material (e.g., fiber cement board or galvanized insect screen at the bottom-edge of openings).
- Foam plastic insulation applied to the interior side of conditioned crawlspace walls should be kept a minimum of 3 in. below the sill plate.

3.2 Provide corrosion-proof rodent/bird screens (e.g., copper or stainless steel mesh) for all building openings that cannot be fully sealed and caulked (e.g., ventilation system intake/exhaust outlets and attic vent openings). This requirement does not apply to clothes dryer vents.

4. HVAC Systems

Heating and Cooling Equipment

4.1 Heating and cooling design loads shall be determined for each room according to ACCA Man J, ASHRAE Handbooks, or equivalent software. Heating and cooling equipment shall be properly sized and selected to meet the design loads and accommodation must be made for pressure drop from specified filter (see Specification 4.7). This requirement shall be met by an ENERGY STAR HVAC QI Certificate (where available) OR verification of all the following:

- Documentation of design load calculations (i.e., load calculation worksheet or software report), AND
- System design documentation (i.e., sizing calculations and equipment performance information), AND
- Verification that outdoor and indoor coils match in accordance with the AHRI Directory of Certified Product Performance (ahridirectory.org).

4.2 Duct system(s) shall be designed according to ACCA Man D, ASHRAE Handbooks, or equivalent software AND installed to be substantially airtight, properly balanced, and protected from construction debris. This requirement shall be met by an ENERGY STAR HVAC QI Certificate (where available) OR verification of all the following prescriptive requirements, OR the Performance Test Alternative below:

- Design verified by appropriate documentation (i.e., duct-sizing worksheet or annotated layout), AND
- Duct system verified to meet the following additional requirements:
  - Seams in the HVAC cabinet, plenum, and adjacent ductwork shall be sealed with mastic systems, tape that meets the applicable requirements of UL 181A or UL 181B, or gasket systems.
  - Building cavities shall not be used as part of the forced air supply or return systems.
- Duct openings shall either be covered during construction or vacuumed out thoroughly prior to installing registers, grilles, and diffusers (see Specification 7.1).

Performance Test Alternative:

- Room-by-room airflows balanced and verified within +/-20% of calculated room airflows to meet design loads (see Specification 4.1), except for baths, closets, and pantries, AND
- Duct system TOTAL leakage test no greater than 6 cfm per 100 s.f. of floor area (or 9% design fan flow), measured at 25 Pa, with duct boots and air handler in place, according to ASTM E1554, ASHRAE 152, or other RESNET-approved method.

4.3 No air-handling equipment or ductwork shall be located in garages.

Note:

Ducts and equipment may be located in framing spaces or building cavities adjacent to garage walls or ceilings if they are separated from the garage space with a continuous air barrier (see ENERGY STAR Thermal Bypass Checklist Guide).

4.4 ***Room pressure differentials shall be minimized by installing transfer grilles or jump ducts for any closed room that does not have a dedicated return, except for baths, kitchens, closets, pantries, and laundry rooms.*** The opening size shall be 1 square in. capacity (grille area) per cfm of supply (including free area undercut below door as part of the area).

Performance Test Alternative:
Measured pressure differential no greater than 3 Pa (0.012 in. w.c.) between closed rooms and adjacent spaces that have a return.

Ventilation

4.5 ***Provide mechanical whole-house ventilation meeting all ASHRAE 62.2 requirements.*** The following requirements shall be visually verified:

- Whole house mechanical ventilation system & controls shall be installed to deliver the prescribed outdoor air ventilation rate (ASHRAE 62.2 section 4), including ventilation restrictions in ASHRAE 62.2 section 4.5 (e.g., not greater than 7.5 cfm/100 s.f. in "Warm-Humid" climates as defined by IECC Figure 301.1); AND

- Transfer air (i.e., air from adjacent dwelling units or other spaces such as garages, crawlspaces, or attics) shall not be used to meet ventilation requirements (ASHRAE 62.2 section 6.1); AND

- Outdoor air inlets shall be located a minimum of 10 ft. from contaminant sources (ASHRAE 62.2 section 6.8); AND

- Airflow shall be tested to meet rated fan airflow (at 0.25 in. w.c.) OR verify duct(s) sized according to the requirements of ASHRAE 62.2 Table 7.1 and the manufacturer's design criteria (ASHRAE 62.2 section 7.3).

Note:
Outdoor air ducts connected to the return side of an air handler shall be permitted as supply ventilation only if the manufacturers' requirements for return air temperature are met (e.g., most manufacturers recommend a minimum of 60 °F air flow across furnace heat exchangers).

4.6 ***Provide local exhaust ventilation to the outdoors for known pollutant sources, as follows:***

- Provide local mechanical exhaust ventilation to the outdoors in each bathroom and kitchen, meeting ASHRAE 62.2 section 5 requirements. In addition, all bathroom ventilation fans shall be ENERGY STAR qualified unless multiple bathrooms are exhausted with a multi-port fan.

- Conventional clothes dryers shall be vented to the outdoors. Electric condensing dryers are not vented and shall be plumbed to a drain according to the manufacturer's instructions.

- If a central vacuum system is installed, the system shall be vented outdoors at least 10 ft. from the ventilation system air inlets (see Specification 4.5), or the power/filtration unit shall be installed in the garage according to the manufacturer's instructions.

Air Cleaning and Filtration

4.7 ***Central forced-air HVAC systems shall include a filtration system meeting the following requirements:***

- HVAC filters shall be rated MERV 8 or higher according to ASHRAE 52.2 (at approximately 295 fpm).

- There shall be no visible bypass between the filter and the filter rack.

- The filter access panel shall include gasket material or comparable sealing mechanism to prevent air leakage, and it shall fit snugly against the exposed edge of the installed filter when closed to prevent bypass.

- No air-cleaning equipment designed to produce ozone (i.e., ozone generators) shall be installed.

Advisory:
Filters perform best when the filter rack design includes the following features, which are also included in some manufacturers' filter media boxes:

- Flexible, air-tight (e.g., closed-cell foam) gasket material on the surface that contacts the air-leaving (downstream) side of the filter, AND

- Friction fit or spring clips installed on the upstream side of the filter to hold it firmly in place.

Dehumidification

4.8 ***In "Warm-Humid" climates as defined by IECC Figure 301.1 (i.e., Climate Zone 1 and portions of Zones 2 and 3A below the white line), equipment shall be installed with sufficient latent capacity to maintain indoor relative humidity (RH) at or below 60%.*** This requirement shall be met by either:

- Additional dehumidification system(s), OR

- A central HVAC system equipped with additional controls to operate in dehumidification mode.

Exception:

Climate Zones 4-8, 3B, 3C, and the portions of 3A and 2B above the white line as shown by IECC Figure 301.1.

Advisory:
Although not required to meet this specification, independent dehumidification is recommended in Climate Zones 4A and 3A above the white line as shown in IECC Figure 301.1.

5. Combustion Pollutant Control

Combustion Source Controls

5.1 For combustion space-heating and water-heating equipment located in conditioned spaces:

- Gas-fired furnaces/boilers shall be direct vented, except in Climate Zones 1-3 as shown in IECC Figure 301.1.
- Oil-fired furnaces/boilers shall be power vented or direct vented, except in Climate Zones 1-3 as shown in IECC Figure 301.1.
- Combustion water heaters shall be power vented or direct vented.
- No unvented combustion space-heating appliances shall be permitted.

Exception:
Houses with no combustion heating equipment located in conditioned spaces.

Note:
Unfinished basements and crawlspaces (except raised pier foundations with no walls) and attached garages that are air-sealed to the outside and intended for use as work space or living space, are considered "conditioned spaces" for the purpose of this requirement.

5.2 Fireplaces and other fuel-burning space-heating appliances located in conditioned spaces shall be vented to the outdoors and supplied with adequate combustion and ventilation air according to the manufacturers' installation instructions, AND they shall meet the following energy efficiency and emissions standards and restrictions:

- ***Masonry fireplaces*** are not permitted, with the exception of "masonry heaters" as defined by ASTM E1602 and section 2112.1 of the International Building Code (i.e., fireplaces engineered to store and release substantial portions of heat generated from a rapid burn).
- ***Factory-built, wood-burning fireplaces*** shall meet the certification requirements of UL 127 and emission limits found in the EPA Standard for New Residential Wood Heaters.
- ***Natural gas and propane fireplaces*** shall be power vented or direct vented, as defined by NFPA 54, section 3.3.108, have a permanently affixed glass front or gasketed door, and comply with ANSI Z21.88/CSA 2.33.
- ***Wood stove and fireplace inserts*** as defined in section 3.8 of UL 1482 shall meet the certification requirements of that standard, and they shall meet the emission requirements of the EPA Standards for New Residential Wood Heaters and WAC 173-433-100 (3).
- ***Pellet stoves*** shall meet the requirements of ASTM E1509.
- ***Decorative gas logs*** as defined in K.1.11 of NFPA 54 (National Fuel Gas Code) are not permitted.
- ***Unvented combustion space-heating appliances*** are not permitted.

Advisory:
To minimize the potential for spillage or back-drafting, fireplaces and fuel-burning appliances located in conditioned spaces should be installed in compliance with ASHRAE 62.2 (section 6.4) or by conducting a Worst Case Depressurization Combustion Air Zone (CAZ) Test according to an established protocol.

5.3 All homes equipped with combustion appliance(s) or an attached garage shall have a carbon monoxide (CO) alarm installed in a central location in the immediate vicinity of each separate sleeping zone (e.g., in a hallway adjacent to bedrooms.) The alarm(s) shall be hard-wired with a battery back-up function and placed according to NFPA 720. The alarms shall be certified by either CSA 6.19-01 or UL 2034.

5.4 Reduce exposure to environmental tobacco smoke (ETS) in multi-family buildings by:

- Prohibiting smoking in indoor common areas, specified explicitly in building rental/lease agreements or condo/co-op association covenants and restrictions, AND
- Locating designated outdoor smoking areas a minimum of 25 ft. from entries, outdoor air intakes, and operable windows, AND
- Minimizing uncontrolled pathways for ETS transfer between individual dwelling units by sealing penetrations in the walls, ceilings, and floors of dwelling units, sealing vertical chases adjacent to dwelling units, and applying weather stripping to all doors in dwelling units leading to common hallways.

Attached Garage Isolation

5.5 ***Attached garages shall be isolated from conditioned spaces as follows:***

- Common walls and ceilings between attached garages and living spaces shall be visually inspected to ensure they are air-sealed before insulation is installed.
- All connecting doors between living spaces and attached garages shall include an automatic closer, and they shall be installed with gasket material or be made substantially air-tight with weather stripping.

5.6 ***Attached garages shall include an exhaust fan, with a minimum installed capacity of 70 cfm, rated for continuous operation, and installed to vent directly outdoors.*** If automatic fan controls are installed, they shall activate the fan whenever the garage is occupied and for at least 1 hour after the garage has been vacated.

Advisory:
ENERGY STAR qualified fans are highly recommended.

6. Low-Emission Materials

Note:
The evaluation, certification, and labeling of products for indoor VOC emissions is complex and evolving. EPA has not established threshold levels for indoor VOC emissions from any of the product categories addressed in these specifications. The third-party programs referenced in these specifications include U.S. programs that are designed to reduce indoor human exposure to individual VOCs of potential concern for human health effects, compared to similar products not certified as low-VOC or no-VOC. EPA will consider modifying these specifications to include additional third-party programs as appropriate.

6.1 ***Structural plywood, oriented strand board (OSB), and composite wood products (i.e., hardwood plywood, particleboard, medium density fiberboard [MDF], and cabinetry made with these products) shall be third-party certified for compliance with industry and federal standards, as follows:***

- Structural plywood and OSB shall be certified compliant with PS1 or PS2, as appropriate, and shall be made with moisture-resistant adhesives as indicated by "Exposure 1" or "Exterior" on the American Plywood Association (APA) trademark.
- Hardwood plywood shall be certified compliant with the formaldehyde emissions requirements of ANSI/HPVA HP-1-2004 and U.S. HUD Title 24, Part 3280, OR certified compliant with CA Title 17.
- Particleboard and MDF shall be certified compliant with the formaldehyde emissions requirements of ANSI A208.1 and A208.2, respectively, and U.S. HUD Title 24, Part 3280, OR certified compliant with EPPS CPA 3-08 by the CPA Grademark certification program, OR certified compliant with CA Title 17.
- Cabinetry shall be made with component materials that are certified to comply with all the appropriate standards above OR shall be registered brands or produced in registered plants certified under KCMA's Environmental Stewardship Certification Program (ESP 01-06).

Note:
In California, composite wood products shall be certified compliant with CA Title 17 as appropriate.

6.2 ***Interior paints and finishes, including 90% or more of such products applied to interior surfaces of homes, shall be certified low-VOC or no-VOC by one of the following:***

- Green Seal Standard GS-11, OR
- Greenguard Certification for Paints and Coatings, OR
- Scientific Certification Systems (SCS) Standard EC-10.2-2007, Indoor Advantage Gold, OR
- Master Painters Institute (MPI) Green Performance Standards GPS-1 or GPS-2, OR
- A third-party low-emitting product list based on CA Section 01350, e.g., the CHPS List at chps.net/manual/lem_table.htm.

6.3 ***Carpets and carpet adhesives shall be labeled with, or otherwise documented as meeting, the Carpet & Rug Institute (CRI) Green Label Plus or Green Label testing program criteria.*** Carpet cushion (i.e., padding) shall similarly be certified to meet the CRI Green Label testing program criteria.

7. Home Commissioning

7.1 ***HVAC systems and ductwork shall be verified to be dry and clean and installed according to their design as documented by an ENERGY STAR HVAC QI Certificate (where available) OR as follows:***

- Inspect ductwork before installing registers, grilles, and diffusers to verify it is dry and substantially free of dust or debris, and that there are no disconnects or visible air gaps between boots and framed openings. If duct openings were not covered during construction, thoroughly vacuum out each opening prior to installing registers, grilles, and diffusers.

- Inspect air-handling equipment and verify that heat exchangers/coils are free of dust caused by construction activities (e.g., drywall, floor sanding) AND the filter is new, clean, and meets specified MERV rating (see Specification 4.7). After installation of registers, grilles, and diffusers, verify detectable airflow from each supply outlet.
- Verify the HVAC contractor has documented measured airflow or pressure drop across the cooling coil or heat exchanger within +/- 15% of system design airflow, or the manufacturer-specified operating range, tested according to ASTM E1554, ASHRAE 152, or an equivalent method.
- Verify the HVAC contractor has documented the installation and testing of proper refrigerant charge. This requirement may be met by any of the following methods according to ACCA 5 QI-2007:
    - Superheat method test measurement within 5% of the manufacturer-recommended charge, OR
    - Subcooling method test measurement within 3% of the manufacturer-recommended charge, OR
    - Other equivalent method/tolerance approved by the equipment manufacturer.

Note:

If weather conditions do not meet required test conditions, verify that the builder or contractor has arranged for future testing.

7.2 ***Verify that the home has been ventilated with outside air at the highest rate practical during and shortly after installing products that are known sources of contaminants (e.g., cabinets, carpet padding, and painting) and during the period between finishing and occupancy, meeting ventilation requirements for outdoor air flow and humidity control (see Specifications 4.5 and 4.8).*** If whole house ventilation cannot be scheduled prior to occupancy, advise the buyer to operate the ventilation system at the highest rate it can provide during the first few months of occupancy, meeting the above requirements.

Abbreviations

BOP	Builder Option Package (ENERGY STAR for Homes)
cfm	cubic feet per minute
fpm	feet per minute
ft.	feet
HERS	Home Energy Rating System
HVAC	heating, ventilating, and air-conditioning
IAQ	indoor air quality
in.	inches
mil	common term to describe plastic sheeting thickness; 1 mil equals 0.001 inches
min.	minimum
MERV	Minimum Efficiency Reporting Value; defined in ASHRAE 52.2
Pa	Pascals
QI	Quality Installation (ENERGY STAR HVAC QI)
s.f.	square feet
spec	specification
TBC	Thermal Bypass Checklist (ENERGY STAR for Homes)
VOC	Volatile Organic Compound
w.c.	water column

7.3 ***Provide for buyers a completed checklist and other required documentation about the IAQ features of their home, including:***

- A copy of the Indoor airPLUS verification checklist or other written documentation indicating compliance with all required measures from the Indoor airPLUS construction specifications, signed by an official representative of the builder, AND
- HVAC, duct, and ventilation system design documentation (i.e., airflow requirements) or performance test results (i.e., measured cfm) required by Specifications 4.1, 4.2, and 4.5, respectively, and a description of the ventilation system (i.e., system type, components, and controls), AND
- Operations and maintenance instruction manuals for all installed equipment and systems addressed by Indoor airPLUS requirements, including HVAC systems and accessories, combustion appliances, and radon system literature and test kit instructions.

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Climate Zones Throughout the Continental United States

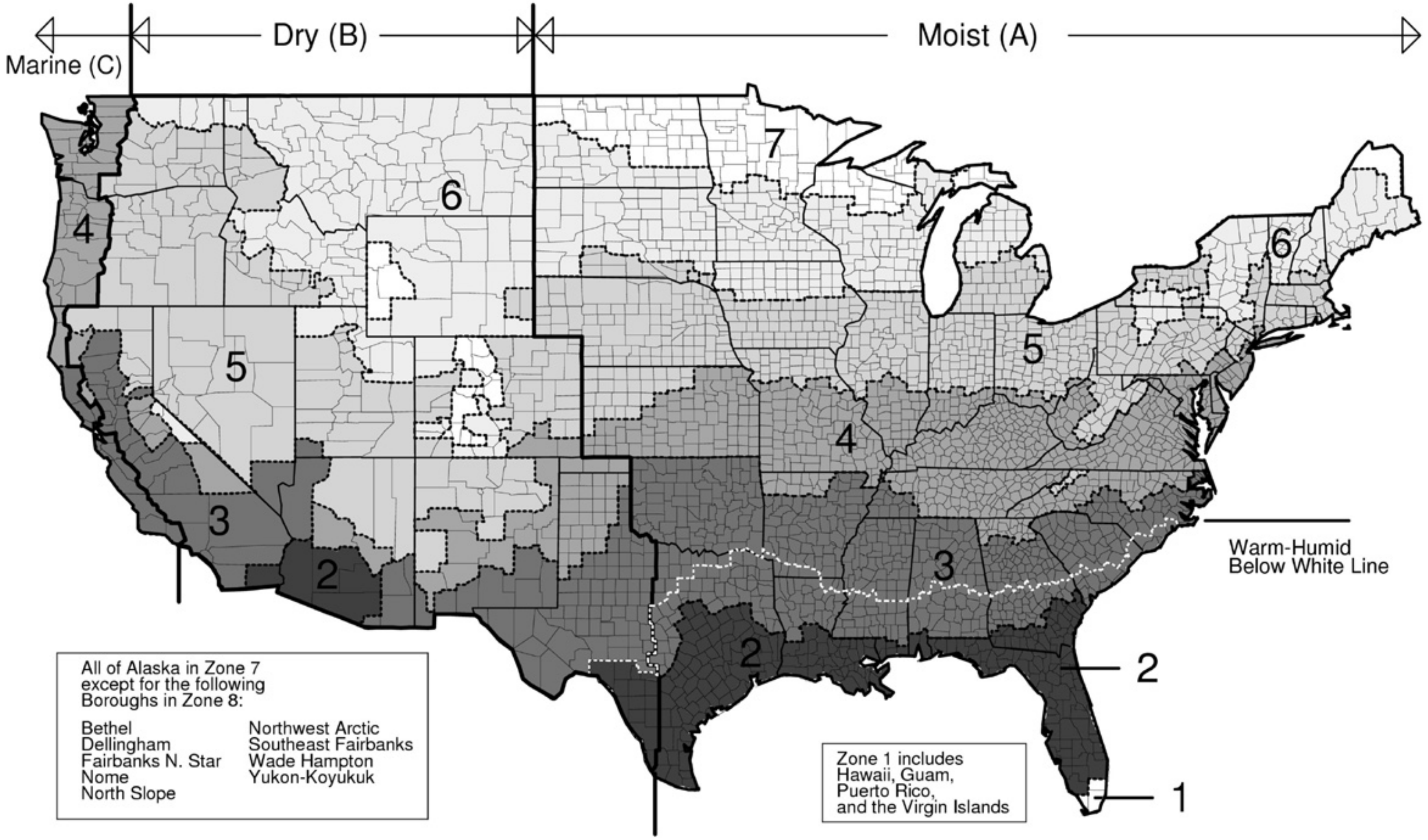

Figure 301.1, 2006 International Energy Conservation Code®

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NHBC Foundation publications

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This research report is the result of a study examining the options for satisfying the requirements of the Building Regulations. It addresses layout, size, travel distances, enhanced detection options and sprinkler use. In addition it addresses the human implications, including the various reactions, wake up and response times from people occupying the building. ***NF19*** September 2009

Zero carbon compendium – Who's doing what in housing worldwide
The Zero Carbon Compendium, produced in association with the Zero Carbon Hub and PRP, is a study of energy and sustainability standards around the world, which allows the UK's plans for zero-carbon housing to be considered from an international perspective. Fifteen countries have been assessed against a framework of questions and presented in a standard format for easy comparison. Case studies for each provide information on the geographic, climatic and statistical indicators for each country as well as a brief review of each country's approach to low- and zero-energy housing. ***NF17*** July 2009

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Indoor air quality in highly energy efficient homes – a review

This review assesses the current state of knowledge on indoor air quality in energy efficient, airtight houses in the UK and elsewhere in the world. It summarises the characteristics of homes built to Levels 4, 5 and 6 homes of the Code for Sustainable Homes, and discusses the relationship between indoor air quality and occupant wellbeing. Research in the UK, Europe and the rest of the world into indoor air quality and other factors which may impact on occupant wellbeing is reviewed. This is followed by a review of current research and state of the art for ventilation performance in dwellings and of construction and ventilation provision in highly energy efficient homes.

Experience of building airtight homes in countries in very cold climates, such as Canada, central Europe, parts of the USA and Scandinavia, provides insights into construction practices that may be increasingly adopted in the UK. However, direct transfer of knowledge is problematic and there is a dearth of information about indoor air quality in highly energy efficient structures. Requirements for research into the performance of highly energy efficient homes and the quality of the internal environment ventilation systems, and the impact on the health and wellbeing of occupants, are identified.

The review is based on an extensive literature review of over 100 references and publications, and includes appendices relating to the Code for Sustainable Homes, PassivHaus, Canadian R-2000TM homes, and the US EPA Indoor airPLUS specification.

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The NHBC Foundation has been established by NHBC in partnership with the BRE Trust. It facilitates research and development, technology and knowledge sharing, and the capture of industry best practice. The NHBC Foundation promotes best practice to help builders, developers and the industry as it responds to the country's wider housing needs. The NHBC Foundation carries out practical, high quality research where it is needed most, particularly in areas such as building standards and processes. It also supports house builders in developing strong relationships with their customers.

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